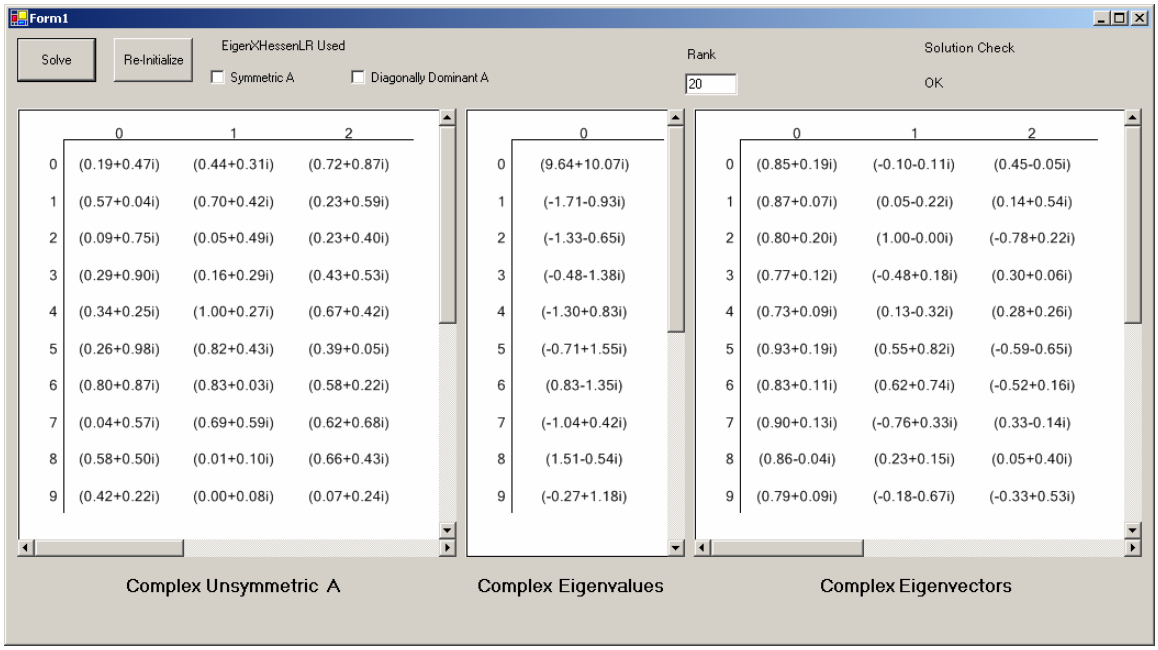
QCMatPack Matrix and Numerical Analysis Software for .Net



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Revision Date 10/06/2007 Rev. 1.0

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1. Introduction to QCMatPack

Tutorials

A simple tutorial that describe how to get started with the QCMatPack for *.Net* charting software are found in Chapter 12 (*Using QCMatPack for .Net to Create Windows and Asp.Net Applications*).

QCMatPack for *.Net* Background

Numerical analysis is the art of calculating solutions to mathematical problems involving real and complex numbers. Man has been trying to measure and calculate his physical world since at the least the beginning of recorded history. Ancient Egypt and Summeria/Babylonia are examples of cultures that required sophisticated numerical methods routines in order to support the construction, religious and agricultural aspects of their societies.

The numerical algorithms in this software package all reside in the realm of continuous mathematics and use both real, and in many cases, complex numbers. Real numbers in this software are approximated using 8-byte *double* numeric objects, with complex numbers requiring two *double* objects. It is the goal, and art of numerical programming, to minimize the negative effects, and accumulated errors, resulting from the imperfect representation of infinite precision real numbers by finite precision floating point numbers.

Numerical algorithms involving statistics, the solution of equations, eigenvalues and digital signal processing were among the first developed for use on computers. Starting in the 1950's, these algorithms were primarily developed in FORTRAN (short for **For**mula **Tran**slating System*)* and starting in the 1960's, ALGOL (short for **ALGO**rithmic **L**anguage). The FORTRAN implementations seem to have won out, even though ALGOL's structured programming elements made it the superior language for algorithm expression. Most of the major, well known, numerical methods libraries, for execution on super, mainframe and even microprocessor-based computers are written in FORTRAN. These include EISPACK, LINPACK, LAPACK, BLAS, SLATEC and MINPACK. In many cases, algorithms were translated from ALGOL, into FORTRAN, often obscuring the logic and flow of the original algorithm. FORTRAN versions of the BLAS and LAPACK libraries are still used today in compiled form with modern computer languages. You are able to find C++ versions of these libraries that are nothing more than C++ wrappers around the original compiled FORTRAN code. You will even find these compiled libraries used with the .Net languages, C# and VB, passing data through an interface that permits mixing unmanaged compiled libraries with managed, .Net code. The result, though, cannot be considered "managed" code.

This software implements what we consider the most useful numerical algorithms, written entirely in C#, with no calls to external libraries that do not utilize the .Net

managed memory system. That includes routines for the generalized solution of linear algebra problems, and specific algorithms for solutions of linear equations, eigensystems, digital signal processing, multiple regression, and curve fitting. Since the algorithms are implemented using 100% managed code, they are the better choice for workstation and web based .Net applications.

Many of the algorithms in science and engineering require the use of complex numbers in the form **a + b*i***, where **a** and **b** are real numbers and ***i*** represents the square root of -1. The .Net runtime, at this time, does not include a numeric type, or object class that supports complex numbers and math; therefore one (**DComplex**) is included with this software. Building on the .Net standard ***double*** numeric type, and our **DComplex** complex number class, two generalized matrix and linear algebra classes (**DDMat** and **DXMat**) were created. The numerical algorithms were then implemented using those matrix classes for input and output.

QCMatPack for .*Net* Dependencies

The **QCMatPack for .*Net*** class library is self-contained. It uses only standard classes that ship with the Microsoft .Net API. The software uses the major .Net namespaces listed below.

System.Windows.Forms Namespace

The **System.Windows.Forms** namespace contains classes for creating .Net Forms, Controls and Dialog boxes.

System.Drawing Namespace

The **QCMatView** matrix viewer classes use the **System.Drawing** namespace. The **System.Drawing** namespace provides access to GDI+ basic graphics functionality. More advanced functionality is provided in the System.Drawing.Drawing2D, System.Drawing.Font, System.Drawing.Imaging, and System.Drawing.Text namespaces.

System.IO Namespace

The IO namespace contains types that allow synchronous and asynchronous reading and writing on data streams and files.

System.Collections Namespace

The **System.Collections** namespace contains interfaces and classes that define various collections of objects, such as lists, queues, bit arrays, hash tables and dictionaries.

.

Directory Structure

The QCMatPack for ***.Net*** class library uses the following directory structure:

Drive:

Quinn-Curtis\ - Root directory

DotNet\ - Quinn-Curtis .Net based products directory

Docs\ - Quinn-Curtis .Net related documentation directory

Lib\ - Quinn-Curtis .Net related compiled libraries and components directory

QCMatPack\ - Language specific code directory

Visual CSharp\ - C# specific directory

QCMatPackLib\ - contains the source code to the QCMatPackNet.dll library (installed only if the source code has been purchased)

QCMatViewLib\ - contains the source code to the QCMatViewNet.dll library (installed only if the source code has been purchased)

Examples\ - C# examples directory

ComplexMath – A simple example demonstrating the use of the **DComplex** complex number class.

QCMatPackExample1 - The tutorial example program.

EigenRealSym\ - Eigenvalue/Eigenvector solutions for real symmetric matrices using the Householder QL and Hessen QR algorithms.

EigenRealUnsym\ - Eigenvalue/Eigenvector solutions for real unsymmetric matrices using the Hessen QR algorithm.

EigenComplex\ - Eigenvalue/Eigenvector solutions for complex matrices.using the Hessen LR algorithm.

SimpleLES\ - A very simple example demonstrating the solution of systems of equations using real numbers.

LESTest\ - Solving systems of equations (real numbers) using Cholesky, LU Decomposition, QR Factorization and Gauss-Jordan algorithms.

SimpleLESX\ - A very simple example demonstrating the solution of systems of equations using complex numbers.

XLESTest\ - Solving systems of equations (complex numbers) using Cholesky, LU Decomposition, QR Factorization and Gauss-Jordan algorithms.

MulRegTest\ - A multiple regression test program.

StepRegTest\ - A stepwise multiple regression test program.

CurveFitTest\ - Curve fitting solutions using polynomial curve fitting

CubicSplinesTest\ - Discrete function approximation using cubic splines.

FFTTest\ - Calculating FFTs and related functions

TCLinTest\ - A thermocouple linearization program.

MatErrorTest\ - Demonstration of QCMatPack error handling

ASPNetExample \ - Holds the WebForm1 file for a simple Asp.Net application

Visual Basic\ - VB specific code

Examples\ - VB examples

ComplexMath – A simple example demonstrating the use of the **DComplex** complex number class.

QCMatPackExample1 - The tutorial example program.

EigenRealSym\ - Eigenvalue/Eigenvector solutions for real symmetric matrices using the Householder QL and Hessen QR algorithms.

EigenRealUnsym\ - Eigenvalue/Eigenvector solutions for real unsymmetric matrices using the Hessen QR algorithm.

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TCLinTest\ - A thermocouple linearization program.

MatErrorTest\ - Demonstration of QCMatPack error handling

ASPNetExample \ - Holds the WebForm1 file for a simple Asp.Net application

There are two versions of the **QCMatPack** class library: the 30-day trial versions, and the developer version. Each version has different characteristics that are summarized below:

30-Day Trial Version

The trial version of **QCMatPack** for ***.Net*** is downloaded as a zip file named Trial_QCMatPackR1x7x.zip. Once you download the zip file, you un-zip it to a local hard drive and run the Setup.exe program from the resulting QCMatPackInstall folder. The 30-day trial version stops working 30 days after you run the Setup.exe program for the first time.

Developer Version

The developer version of QCMatPack for ***.Net*** is downloaded as a zip file, name something similar to NETMATDEV1R1x0x353x1.zip. Once you download the zip file, you un-zip it to a local hard drive and run the Setup.exe program from the resulting QCMatPackInstall folder. You can use your original download links to download free updates for a period of 2-years.

Chapter Summary

The remaining chapters of this book discuss the **QCMatPack for *.Net*** numerical analysis software designed to run on any hardware that has .Net or higher interpreter, available for it.

Chapter 2 presents the overall class architecture of the **QCMatPack for *.Net*** and summarizes all of the classes found in the software.

Chapter 3 describes complex number class used throughout the software.

Chapter 4 describes the real and complex number matrix classes that you will use to get data in and out of the numerical analysis routines.

Chapter 5 describes the classes that solve systems of linear equations for real and complex numbers. Algorithms include Cholesky, LU Decomposition, QR Factorization and Gauss-Jordan.

Chapter 6 describes the general eigenvalue and eigenvector problem**.** Algorithms are presented for matrices that are real-symmetric (QL and QR), real-unsymmetric (QR), and complex. (LR).

Chapter 7 describes a least squares multiple regression class that handles multiple regression and stepwise multiple regression, along with related regression summary statistics.

Chapters 8 describes a curve-fitting class that handles polynomial, exponential, rational polynomial and mixed curve-fitting. It also describes a cubic splines class.

Chapters 9 describes a digital signal processing class (DSP) that solves for real and complex FFT's, power spectrums, and related parameters.

Chapters 10 describes the matrix viewer controls used to display real and complex matrices in a Windows form.

Chapters 11 describes a thermocouple linearization class based on the most current standards: NIST ITS-90.

Chapter 12 discussed errors that the software can generate and the various error processing modes.

Chapter 13 is a tutorial that describes how to use **QCMatPack** to create Windows applications using Visual Studio .Net, Visual C# and Visual Basic.

2. Class Architecture of QCMatPack

Major Design Considerations

This chapter presents an overview of the **QCMatPack for .*Net*** class architecture. It discusses the major design considerations of the architecture:

- **QCMatPack** is 100% managed code, using only the .Net core numeric routines in the matrix and numerical analysis classes. The software makes NO calls to external, non-.Net based libraries.

- Simple to use matrix and numerical analysis classes for the most common problems in science, engineering, industry, and business.

- There are no limits regarding the size of vectors and matrices, other than the amount of free memory on the host computer. There are no limits regarding the size of the vectors and matrices used in the solution of general linear systems, solution of eigenvalue problems, multiple regression, curve fitting and DSP (FFT) routines.

The chapter also summarizes the classes in the **QCMatPack for .*Net*** library.

There are four primary features of the overall architecture of the **QCMatPack for .*Net*** classes. These features address major shortcomings in existing numerical software for use with both .Net and other computer languages.

- First, **QCMatPack** implements a complex number class, **DComplex**, that provides a data structure, functions and operators for manipulating complex numbers. Operator overloading of the +, -, *, /, (etc.) operators make manipulating complex numbers as simple as possible.

- Second, **QCMatPack** implements several generalized matrix classes, the most important of which are the **DDMat** for real number matrices and the **DXMat** class for complex number matrices. These are used for the input and output of data to the numerical analysis routines and the manipulation of real and complex number matrices. The matrix classes are designed so that there is no practical limit, other than the amount of free system memory, to the size of matrices. The **DDMat** and **DXMat** are symmetrical, in that the same matrix math and linear algebra routines are available for both real and complex numbers.

- Third, the library implements the best of the algorithms we could find in numerical analysis. These include LU Decomposition, QR Factorization, Cholesky and Gauss-Jordan for the solution of real and complex linear systems; QL, QR, and LR routines for the solution of real and complex eigenvalue/eigenvector problems; FFT's for real

and complex data, multiple; and stepwise multiple regression, curve fitting, and thermocouple linearization.

- Fourth, a pair of matrix viewer controls, one for real (**DMatViewer**) and the other for complex matrices (**XMatViewer**), let you add scrollable matrices to your Windows form-based application programs.

QCMatPack for .*Net* Class Summary

The following categories of classes realize these design considerations.

Complex number class

The **DComplex** class implements a complex number class using a pair of doubles to hold the real and imaginary parts of a complex number. Extensive support for support of complex numeric functions and operator overloading, including conjugate, +, -, +, /, magnitude, power, exponent, and square root functions.

Matrix classes

Two matrix classes, **DDMat** for real numbers, and **DXMat** for complex numbers, simplify data manipulation and the input/output of data to/from the numerical analysis routines.

Solution of linear systems

There is a symmetrical group of eight classes for the solution of real and complex linear systems. These classes correspond to real and complex versions of Cholesky factorization (**LESCholesky**, **LESXCholesky**), LU Decomposition (**LESLU**, **LESXLU**), QR Factorization (**LESQR**, **LESXQR**) and Gauss-Jordan (**LESGJ**, **LESXGJ**). Each class provides for the solution of one right hand side, multiple right hand sides and matrix inverse.

Solution of eigensystems

The eigensystem problem is divided into three categories real-symmetric, real-unsymmetric and complex (both symmetric (Hermitian) and complex unsymmetric. The real-symmetric case is handled using the QL class **EigenQL**. The **EigenQR and EigenQR2** classes solve the real-unsymmetric case. And the **EigenXLR** class will solve general complex eigenvalue problems.

Multiple regression

General multiple regression, forward regression, backward regression, stepwise multiple and split regression and regression summary statistics are found in the **MulReg, StepwiseMulReg and SplitMulReg** classes.

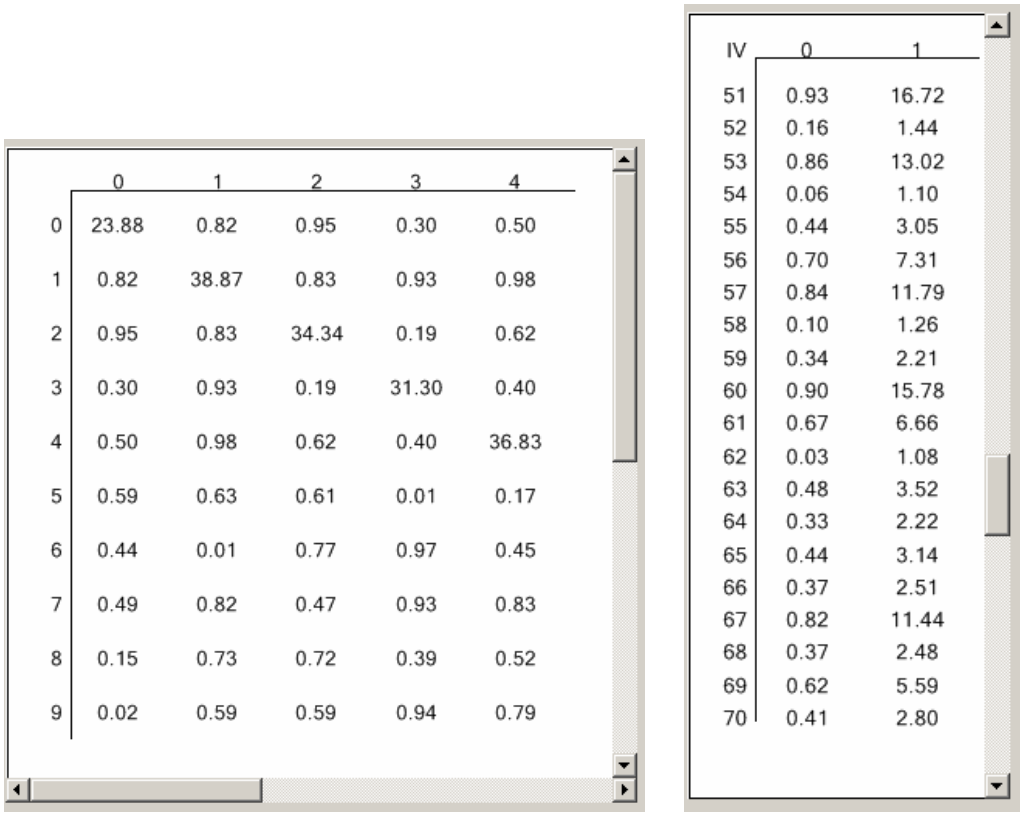
Curve fitting	The **CurveFit** class includes support for polynomial, exponential, rational polynomial, and mixed curve fitting. The **CubicSplines** class uses a cubic splines algorithm for discrete function evaluation.
Digital signal processing	The **DSP** class includes routines for real and complex FFT's and power spectrum calculations. Auxiliary routines calculate FFT magnitudes, phases and frequencies.
Matrix viewer classes	The **DMatViewer** and **XMatViewer** classes are **UserControl** subclasses that display real and complex number matrices, respectively.
Thermocouple linearization	The thermocouple linearization routines will convert from millivolts to temperature and temperature to millivolts, for B, E, J, K, N, R, S, T thermocouple types. Calculations are is based on the NIST ITS-90 standard as published in the NIST Monograph 175.

A summary of each category appears in the following section.

Matrix Viewer Classes

System.Windows.Forms.UserControl
    MatView
        DMatViewer
        XMatViewer

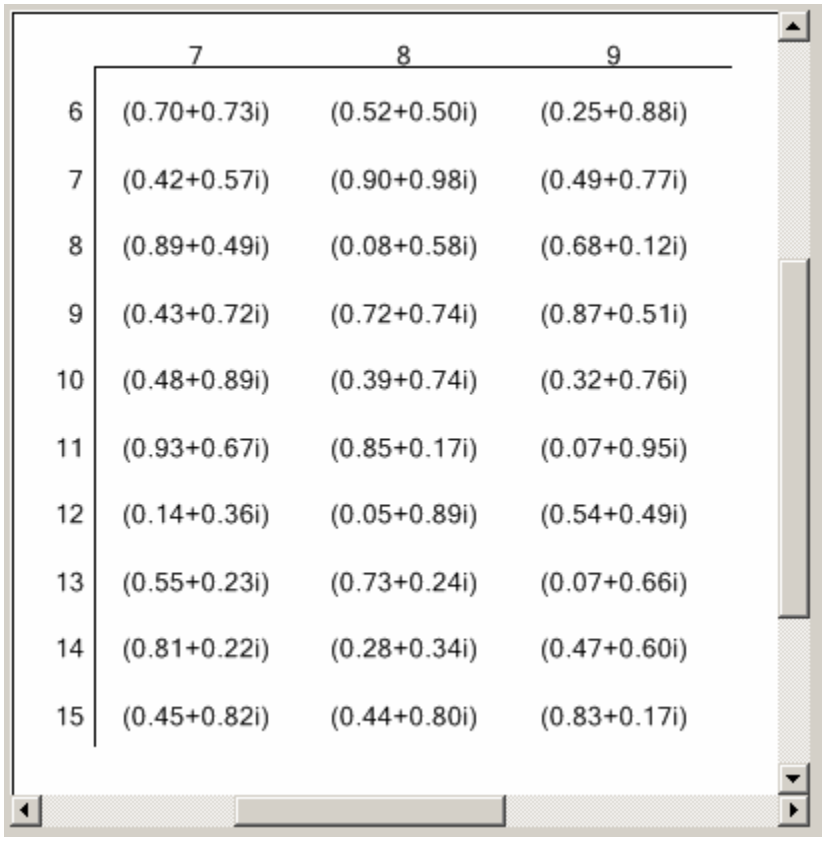
The matrix viewer classes display a matrix in a .Net **UserControl** derived object. As such, it can be placed, and resized anywhere on a .Net **System.Windows.Forms.Form** form. If the matrix is larger than the size you have created the view, scrollbars give the option of scrolling the rows and columns of the matrix. The **DMatViewer** class displays real matrix while the **XMatViewer** displays a complex matrix. The matrix viewers include options to edit matrix values, change font characteristics, the numeric format of the matrix element values, and the number of displayed rows and columns.



	0	1	2	3	4
0	23.88	0.82	0.95	0.30	0.50
1	0.82	38.87	0.83	0.93	0.98
2	0.95	0.83	34.34	0.19	0.62
3	0.30	0.93	0.19	31.30	0.40
4	0.50	0.98	0.62	0.40	36.83
5	0.59	0.63	0.61	0.01	0.17
6	0.44	0.01	0.77	0.97	0.45
7	0.49	0.82	0.47	0.93	0.83
8	0.15	0.73	0.72	0.39	0.52
9	0.02	0.59	0.59	0.94	0.79

IV	0	1
51	0.93	16.72
52	0.16	1.44
53	0.86	13.02
54	0.06	1.10
55	0.44	3.05
56	0.70	7.31
57	0.84	11.79
58	0.10	1.26
59	0.34	2.21
60	0.90	15.78
61	0.67	6.66
62	0.03	1.08
63	0.48	3.52
64	0.33	2.22
65	0.44	3.14
66	0.37	2.51
67	0.82	11.44
68	0.37	2.48
69	0.62	5.59
70	0.41	2.80

DMatViewer displays matrix elements of a DDMat (real) matrix



	7	8	9
6	(0.70+0.73i)	(0.52+0.50i)	(0.25+0.88i)
7	(0.42+0.57i)	(0.90+0.98i)	(0.49+0.77i)
8	(0.89+0.49i)	(0.08+0.58i)	(0.68+0.12i)
9	(0.43+0.72i)	(0.72+0.74i)	(0.87+0.51i)
10	(0.48+0.89i)	(0.39+0.74i)	(0.32+0.76i)
11	(0.93+0.67i)	(0.85+0.17i)	(0.07+0.95i)
12	(0.14+0.36i)	(0.05+0.89i)	(0.54+0.49i)
13	(0.55+0.23i)	(0.73+0.24i)	(0.07+0.66i)
14	(0.81+0.22i)	(0.28+0.34i)	(0.47+0.60i)
15	(0.45+0.82i)	(0.44+0.80i)	(0.83+0.17i)

XMatViewer displays matrix elements of a DXMat (complex) matrix

Complex number class

DComplex

In mathematics, a **complex number** is a number of the form

$$a + bi$$

where *a* and *b* are real numbers, and *i* is the imaginary unit, with the property $i^2 = -1$. The real number *a* is called the *real part* of the complex number, and the real number *b* is the *imaginary part*. Real numbers may be considered to be complex numbers with an imaginary part of zero; that is, the real number *a* is equivalent to the complex number *a*+0*i*. (source Wikipedia).

This software represents a complex number using the **DComplex** class. It represents the real and imaginary parts of a complex number using two *double* values. It includes overrides of the most common math operators (+, -, *, /, =), making it very simple and logical to write mathematical expressions using complex numbers. For example, the following line in bold is a valid expression involving **DComplex** complex number arguments.

```
DComplex a1 = new DComplex(3,2);
DComplex a2 = new DComplex(7.1, -1.5);
DComplex a3 = new DComplex(-17, 7);

DComplex a4 = ((a1 - a2) * (a1 + a2))/a3;
```

The **DComplex** class also includes a large number of mathematical functions used in conjunction with complex numbers (Conjugate, Magnitude, Abs, Sqrt, Exp, Pow, and Arg).

The **DXMat** class is the main class used to represent vectors and matrices of **DComplex** complex numbers. The linear equations classes: **LESXLU**, **LESXGJ**, **LESXCholesky** and **LESXQR,** are specific to the **DComplex** complex number type. The eigensystem classes: **EigenQR2**, **EigenXLR,** also uses the **DComplex** number type.

Matrix Classes

MatBase
- **DMatBase**
  - **DDMat**
- **XMatBase**
  - **DXMat**

The **MatBase** abstract base class is the base class for all matrix types. The **DMatBase** class is the abstract representation of a real matrix. The **DDMat** class is the concrete representation of a real matrix, using doubles for numeric storage. The **XMatBase** class is the abstract representation of a complex number matrix. The **DXMat** class is the concrete representation of a complex number matrix, using **DComplex** objects for numeric storage.

MatBase

The **MatBase** abstract base class is the base class for all matrix types. It defines the dimensions of a matrix, usually referred to as m x n, representing the number of rows and

columns of a matrix. It also contains numeric constants commonly used in matrix math routines.

DMatBase — The **DMatBase** class is the abstract representation of a real matrix. It contains a large number of methods specific to real matrices. At this time, the only matrix class that derives from **DMatBase** is the concrete matrix class **DDMat**. Future versions of the software may define one or more real sparse matrix classes derived from **DMatBase**.

XMatBase — The **XMatBase** class is the abstract representation of a complex matrix. It contains a large number of methods specific to complex matrices. At this time, the only matrix class that derives from **XMatBase** is the concrete matrix class **DXMat**. Future versions of the software may define one or more complex sparse matrix classes derived from **XMatBase**.

DDMat — The **DDMat** class is the concrete representation of a real matrix, using doubles for numeric storage. It contains a large number of matrix manipulation methods optimized for dense double storage. It also includes operator overloads (+, -, *, /, etc.) that permit matrix math expressions of the type X = (A + B * C)/D, where X, A, B, C and D are **DDMat** objects that follow the rules of matrix math, i.e. you do have to get the rows and column orders right.

DXMat — The **DXMat** class is the concrete representation of a complex matrix, using **DComplex** objects for numeric storage. It contains a large number of matrix manipulation methods optimized for dense **DComplex** object storage. It also includes operator overloads (+, -, *, /, etc.) that permit matrix math expressions of the type X = (A + B * C)/D, where X, A, B, C and D are **DXMat** objects that follow the rules of matrix math, i.e. you do have to get the rows and column orders right

Solution of Linear Systems

LESBase

- **LESLU**
- **LESGJ**
- **LESCholesky**

LESQR
LESXBase
LESXLU
LESXGJ
LESXCholesky
LESXQR

A system of linear equations is defined by the linear algebra equation:

$$Ax = b$$

where A, x and b represent real/complex matrices. A is the known coefficient matrix, b is the known right hand side, and x is the unknown solution. A is usually square, though in the case of the QR algorithm A can be over determined where the number of rows is greater than the number of columns. The matrices x and b are usually column matrices of one column, though in the case of multiple right hand sides, both x and b can have multiple columns.

This software provides a symmetrical group of classes for the solution of real and complex linear systems.

LESBase This class is the abstract base class for linear equation solvers that use real numbers. It defines a standard interface for solving systems of equations that involve one or more right hand sides.

LESXBase This class is the abstract base class for linear equation solvers that use complex numbers. It defines a standard interface for solving systems of equations that involve one or more right hand sides.

There are eight concrete classes, derived from **LESBase** and **LESXBase**, corresponding to real and complex versions of Cholesky factorization (**LESCholesky**, **LESXCholesky**), LU Decomposition (**LESLU**, **LESXLU**), QR Factorization (**LESQR**, **LESXQR**) and Gauss-Jordan (**LESGJ**, **LESXGJ**). Each class provides for the solution of one right hand side, multiple right hand sides and the matrix inverse.

LESLU The **LESLU** class uses the LU decomposition algorithm to solve a system of real number linear equations**.** It is a very stable, efficient, method of solving systems of equations. It is particularly useful for solving systems of equations involving multiple right hand sides, since the LU decomposition of the primary coefficient matrix only needs to be solved for once. From that point on, multiple right

hand sides can be solved for using the decomposed matrix and simple back-substitution.

LESXLU The **LESXLU** class is the complex number version of the **LESLU** class, using the LU decomposition algorithm to solve a system of complex number linear equations**.**

LESGJ The **LESGJ** class uses the Gauss-Jordan with partial pivoting algorithm to solve a system of real number linear equations**.** It is a very stable, efficient, method of solving systems of equations.

LESXGJ The **LESXGJ** class is the complex number version of the **LESGJ** class, using the Gauss-Jordan with partial pivoting algorithm to solve a system of complex number linear equations**.**

LESCholesky The **LESCholesky** class uses the Cholesky decomposition algorithm to solve a system of real number linear equations**.** The Cholesky algorithm requires that the coefficient matrix is a symmetrical (where the elements below the diagonal are the transpose of the elements above the diagonal), positive definite, matrix. It turns out that this class of matrices are quite common in systems of equations, so this algorithm should be given special consideration. It is up to twice as fast as LU decomposition and four times as fast as Gauss-Jordan. Like LU decomposition, it is particularly useful for solving systems of equations involving multiple right hand sides, since the Cholesky decomposition of the primary coefficient matrix only needs to be solved for once. From that point on, multiple right hand sides can be solved for using the decomposed matrix and simple back-substitution.

LESXCholesky The **LESXCholesky** class is the complex number version of the **LESCholesky** class, using the Cholesky decomposition algorithm to solve a system of complex number linear equations**.** The complex version of the Cholesky algorithm requires that the source coefficient matrix is Hermitian (the complex version of a symmetric matrix, where the elements below the diagonal are the complex conjugate of the elements above the diagonal, and the diagonal is real), positive and definite.

LESQR The **LESQR** class uses the QR factorization algorithm to solve a system of real number linear equations**.** It is a very stable, efficient, method of solving systems of equations. It

has one major advantage over the other equation solvers, in that it works with both square, and an over-determined (where the number of rows is greater than the number of columns, m > n) coefficient matrices. Like the LU and Cholesky algorithms, it is efficient at solving multiple right hand sides, since the QR factorization of the primary coefficient matrix only needs to be solved for once. From that point on, multiple right hand sides can be solved for using the factored matrix and simple back-substitution.

LESXQR — The **LESXQR** class is the complex number version of the **LESQR** class, using the QR factorization algorithm to solve a system of complex number linear equations**.**

Solution of Eigensystems

EigenBase
- **EigenQL**
- **EigenQR**
- **EigenQR2**

EigenXBase
- **EigenXLR**

The classes above implement algorithms for the solution of real and complex eigensystems. The **EigenBase** class is the abstract representation of an eigensystem solver that starts with a coefficient matrix of real numbers. The **EigenXBase** class is the abstract representation of an eigensystem solver that starts with a coefficient matrix of complex numbers.

EigenBase — This class is the abstract base class for eigensystem solvers that start with real coefficient matrix. It defines a standard interface for solving for eigenvalues and eigenvectors for real, symmetric and unsymmetric matrices.

EigenXBase — This class is the abstract base class for eigensystem solvers that start with complex coefficient matrix. It defines a standard interface for solving for eigenvalues and eigenvectors for complex, symmetric (Hermitian) and unsymmetric (un-Hermitian) matrices.

.

There are four concrete classes, derived from **EigenBase** and **EigenXBase**, that solve for all general categories of the initial eigensystem matrix: real-symmetric, real-

unsymmetric, complex-symmetric (Hermitian actually) and complex unsymmetric (non-Hermitian.).

EigenQL Use this class to solve for the eigenvalues and eigenvectors of real, symmetric, matrices. It uses the implicit QL algorithm and can solve real-symmetric eigensystem problems, which generate real-only eigenvalue and eigenvector solutions.

EigenQR Use this class to solve for the real and/or complex eigenvalues of general (not necessarily symmetric), real, matrices. The QR algorithm can solve general eigensystem problems, that generate both real and complex eigenvalue and eigenvector solutions.

EigenQR2 Use this class to solve for the real and/or complex eigenvalues and eigenvectors of general real matrices. It uses the QR algorithm and can solve general (symmetric and non-symmetric) eigensystem problems, which generate complex eigenvalue and eigenvector solutions.

EigenXLR Use this class to solve for the eigenvalues and eigenvectors of general complex matrices. It uses the LR algorithm and can solve general (Hermitian and non-Hermitian) eigensystem problems, which generate complex eigenvalue and eigenvector solutions.

Multiple Regression

MulReg
- **StepwiseMulReg**
- **SplitMulReg**

Regression analysis is a statistical tool for the evaluation of the relationship of one or more independent variables X_1, X_2,...,X_k to a single dependent variable Y for a fixed number of observations. The primary goal of regression analysis is to obtain predictions of Y using the known values of X. These predictions are calculated using a regression equation. They are subject to error and are only estimates of the true values of Y. There can be other goals of regression analysis, for example, to determine which of several independent variables are important and which are not for describing and predicting a dependent variable.

The **MulReg** class solves the generalized least-squares multiple regression problem. The **StepwiseMulReg** class includes forward, backward, and stepwise multiple regression algorithms that only includes independent variables (the x-values) in the final solution that pass a F-statistic significance test. The **SplitMulReg** splits the original data into two, develops a model using one dataset and uses that to predict the values in the second dataset.

MulReg	The least-squares multiple regression algorithm calculates the coefficients for a set of specific independent variable (x-values). The method also calculates a large number of parameters describing the quality of the regression: the R value, R-squared value, standard error of the estimate (SEE), the overall F-Stat value, and the standard error and the F-Stat value for each regression equation coefficient.
StepwiseMulReg	The stepwise multiple regression algorithm includes forward, backward and stepwise regression algorithms for automatic selection of regression variables. Stepwise regression removes variables that fail an F-statistic significance test, usually leaving you with fewer variables, and a simpler model, than you started with.
SplitMulReg	The **SplitMulReg** splits the original data into two, develops a model using one dataset and uses that to predict the values in the second dataset.

Curve Fitting

CurveFit
CubicSplines

Experimental data often takes the form of measurements of some kind (temperature or volts for example) taken at discrete and possibly periodic times. In such cases, a table of the measured variable versus time is produced. The goal of the research is to uncover the underlying function f(x) which relates temperature to time. Once the underlying function is discovered (the solution is usually only an approximation of the true function), the function can be used to calculate the values of f(x) (temperature in this case) for x values (points in time) which were not part of the original measured data.

The **CurveFit** algorithms create a single model that is the least squares fit for all the data points in the original dataset. The **CubicSplines** class creates a family of cubic equations, one cubic equation for each sample interval, that can be used to interpolate y-values based on x-values not in the original dataset.

CurveFit — The **CurveFit** algorithm calculates the coefficients for a single equation that fits all of the data points in the original dataset. It supports four different algorithms for curve fitting: polynomial, exponential, rational fraction, and mixed (a combination of the first three methods).

CubicSplines — The **CubicSplines** class creates a family of cubic equations, one cubic equation for each sample interval, that can be used to interpolate y-values based on x-values not in the original dataset.

Digital Signal Processing

DSP

A **fast Fourier transform** (**FFT**) is an efficient algorithm to compute the discrete Fourier transform (DFT) and its inverse. FFTs are of great importance to a wide variety of applications, from digital signal processing and solving partial differential equations to algorithms for quick multiplication of large integers.

The DSP class is built around the Cooley-Tukey radix-2 FFT algorithm. Support routines (windowing, magnitude, frequency and phase calculations) and popular variants (power spectrum calculations, real-only FFTs) are also included.

DSP — The **DSP** class includes methods for **DDMat** (real-only) and **DXMat** (complex) FFT calculations. It also includes static FFT functions that accept double [] array arguments for maximum speed. The raw signal can be processed with a DPS window (NOWIN, RECTANGULAR, GAUSS, HAMMING, HANN, BARTLETT, BARTLETT_HANN, NUTTALL, BLACKMAN_HARRIS, BLACKMAN_NUTTALL, FLATTOP, PARZEN, WELCH, BLACKMAN, KAISER_BESSEL TRIANGULAR, and EXPONENTIAL.) before the FFT, and the FFT results can be interpreted using magnitude, phase, and frequency routines. The **PowerSpectrum** method returns the power spectrum of the original signal.

Miscellaneous Chart Classes

BMTimer
DTriplet
XTriplet
MatError
MatSupport
RegStats
IVect

Various classes exist to support the main matrix and algorithm classes

BMTimer	A simple timer class used to benchmark algorithms in the software. It is based on the system clock and while it has microsecond resolution, its accuracy is only 20 milliseconds.
DTriplet	The **DTriplet** class is used to transfer data to/from real matrices. It specifies a row, column and value.
XTriplet	This **XTriplet** class is the **DComplex** version of **DTriplet**
MatError	Processes errors in the matrix and algorithm classes.
MatSupport	Common functions used by multiple classes are moved into the **MatSupport** class, avoiding duplication.
RegStats	The **RegStats** class is used to return summary statistics for the multiple regression and curve fitting classes.
IVect	IVect is a simple integer vector class used to pass integer data to and from some classes.

Class Hierarchy of QCMatPack

DComplex
MatBase
    DMatBase

DDMat
XMatBase
DXMat
MatViewerBase
DMatViewer
XMatViewer
LESBase
LESLU
LESGJ
LESCholesky
LESQR
LESXBase
LESXLU
LESXGJ
LESXCholesky
LESXQR
EigenBase
EigenQR
EigenQL
EigenQR2
EigenXBase
EigenXLR
MulReg
StepwiseMulReg
SplitMulReg
CurveFit
CubicSplines
DSP
TCLin
BMTimer
DTriplet
XTriplet
MatError
MatSupport
RegStats
IVect

3. Complex Numbers

The linear algebra, solution of linear systems and eigenvalue/eigenvector algorithms in this software come in versions that apply to both real and complex numbers. While the .Net *double* numeric type is what we use for real numbers, .Net does not have a standard equivalent numeric type for complex numbers. To that end we have created our own complex class, **DComplex**, for use in our algorithms and your programs.

DComplex

In mathematics, a **complex number** is a number of the form

$$a + bi$$

where a and b are real numbers, and i is the imaginary unit, with the property $i^2 = -1$. The real number a is called the *real part* of the complex number, and the real number b is the *imaginary part*. Real numbers may be considered to be complex numbers with an imaginary part of zero; that is, the real number a is equivalent to the complex number $a+0i$. (source Wikipedia: http://en.wikipedia.org/wiki/Complex_number)

The **DComplex** class represents the real and imaginary parts of a complex number using two *double* values. It includes overrides of the most common math operators (+, -, *, /, =), making it very simple and logical to write mathematical expressions using complex numbers. For example, the following line in bold is a valid expression involving **DComplex** complex number arguments.

```
DComplex a1 = new DComplex(3,2);
DComplex a2 = new DComplex(7.1, -1.5);
DComplex a3 = new DComplex(-17, 7);

DComplex a4 = ((a1 - a2) * (a1 + a2))/a3;
```

Special note: Visual Basic in Visual Studio 2002 and Visual Studio 2003 do not have the ability to process overloaded operators. This feature is only supported under VB with Visual Studio 2005 and higher. Overloaded operators work with all versions of C#.

The **DComplex** class also includes a large number of mathematical functions used in conjunction with complex numbers (Conjugate, Magnitude, Abs, Sqrt, Exp, Pow, and Arg).

The **DXMat** class is the main class used to represent vectors and matrices of **DComplex** complex numbers. The linear equations classes: **LESXLU**, **LESXGJ**, **LESXCholesky** and **LESXQR,** are specific to the **DComplex** complex number type. The eigensystem classes: **EigenQR** and **EigenQR2**, **EigenXLR**, also uses the **DComplex** number type.

DComplex constructors

Create **a DComplex** object using a pair of doubles, a single double, or another **DComplex** object.

```
[VB] Public Sub New( ByVal re As Double,  ByVal im As Double )
[C#] public DComplex(double re, double im);

[VB] Public Sub New( ByVal re As Double )
[C#] public DComplex( double re);

[VB] Public Sub New( ByVal c As DComplex )
[C#] public DComplex( DComplex c);
```

re The real part of the complex number.

im The imaginary part of the complex number.

You can also specify a complex number using the polar coordinates convention using the **FromPolar** static method.

```
[VB] Public Shared Function FromPolar(ByVal mag As Double,
           ByVal angle As Double ) As DComplex
[C#] public static DComplex FromPolar( double mag,  double angle);
```

Access the real and imaginary part of the complex number using the properties Re and Im.

```
[C#]
DComplex c = new DComplex(1.0, 2.0);
c.Re = 5.0;
c.Im = 7.0;
double r2 = c.Re;
double i2 = c.Im;

[VB]
```

```
Dim c As New DComplex(1.0, 2.0)
c.Re = 5.0
c.Im = 7.0
Dim r2 As Double = c.Re
Dim i2 As Double = c.Im
```

Complex Math Operators

Complex numbers are added, subtracted, multiplied, and divided in a manner analagous to that of real numbers, following the associative, commutative and distributive laws of algebra, together with the equation $i^2 = -1$. Since the standard .Net arithmetic operators (+, -, *, /) do not automatically work with user defined classes, the **DComplex** class overrides these operators so that you can use a mix of **DComplex** and double values in math expressions.

Special note: Visual Basic in Visual Studio 2002 and Visual Studio 2003 do not have the ability to process overloaded operators. This feature is only supported under VB with Visual Studio 2005 and higher. Overloaded operators work with all versions of C#. They are function equivalent to every operator overload (Negate, Add, Subtract, Multiple, Divide, Equals, and NotEquals) that can be used with all .Net versions of VB.

```
public static DComplex operator+
```

$$(a + bi) + (c + di) = (a + c) + (b + d)i$$

```
[C#]
DComplex c1 = new DComplex(1.0, 2.0);
DComplex c2 = new DComplex(3.0, 4.0);
double r1 = 5.0;
DComplex c3 = c1 + c2 + r1 + 6.0;

[VB]
Dim c1 As New DComplex(1.0, 2.0)
Dim c2 As New DComplex(3.0, 4.0)
Dim r1 As Double = 5.0
Dim c3 As DComplex = c1 + c2 + r1 + 6.0
```

```
public static DComplex operator-
```

$$(a + bi) - (c + di) = (a - c) + (b - d)i$$

```
[C#]
DComplex c1 = new DComplex(1.0, 2.0);
DComplex c2 = new DComplex(3.0, 4.0);
```

```
double r1 = 5.0;
DComplex c3 = c1 - c2 + r1 - 6.0;
```

```
[VB]
Dim c1 As New DComplex(1.0, 2.0)
Dim c2 As New DComplex(3.0, 4.0)
Dim r1 As Double = 5.0
Dim c3 As DComplex = c1 - c2 + r1 - 6.0
```

```
public static DComplex operator*
```

$$(a+bi)(c+di) = ac + bci + adi + bdi^2 = (ac - bd) + (bc + ad)i$$

```
[C#]
DComplex c1 = new DComplex(1.0, 2.0);
DComplex c2 = new DComplex(3.0, 4.0);
double r1 = 5.0;
DComplex c3 = c1 * c2 * r1 + 6.0;
```

```
[VB]
Dim c1 As New DComplex(1.0, 2.0)
Dim c2 As New DComplex(3.0, 4.0)
Dim r1 As Double = 5.0
Dim c3 As DComplex = c1 * c2 * r1 + 6.0
```

```
public static DComplex operator/
```

$$(a+bi)/(c+di) = \left(\frac{ac+bd}{c^2+d^2}\right) + \left(\frac{bc-ad}{c^2+d^2}\right)i$$

```
[C#]
DComplex c1 = new DComplex(1.0, 2.0);
DComplex c2 = new DComplex(3.0, 4.0);
double r1 = 5.0;
DComplex c3 = (c1 / c2) / r1 + 6.0;
```

```
[VB]
Dim c1 As New DComplex(1.0, 2.0)
Dim c2 As New DComplex(3.0, 4.0)
Dim r1 As Double = 5.0
Dim c3 As DComplex = (c1 / c2) / r1 + 6.0
```

```
public static DComplex operator=
```

```
[C#]
DComplex c1 = new DComplex(1.0, 2.0);
DComplex c2 = new DComplex(3.0, 4.0);
double r1 = 5.0;
DComplex c3 = (c1 / c2) / r1 + 6.0;

[VB]
Dim c1 As New DComplex(1.0, 2.0)
Dim c2 As New DComplex(3.0, 4.0)
Dim r1 As Double = 5.0
Dim c3 As DComplex = (c1 / c2) / r1 + 6.0
```

Mix all of the operators in complex math expressions

```
[C#]
DComplex c1 = new DComplex(1.0, 2.0);
DComplex c2 = new DComplex(3.0, 4.0);
DComplex c3 = new DComplex(5.0, 6.0);
DComplex c4 = new DComplex(7.0, 8.0);
double r1 = 9.0;
DComplex c5 = ((((c1 / c2)* c3) + 11.0)/ c4) - r1;

[VB]
Dim c1 As New DComplex(1.0, 2.0)
Dim c2 As New DComplex(3.0, 4.0)
Dim c3 As New DComplex(5.0, 6.0)
Dim c4 As New DComplex(7.0, 8.0)
Dim r1 As Double = 9.0
Dim c5 As DComplex = (c1 / c2 * c3 + 11.0) / c4 - r1
```

Once the +, -, * and / operators are overwritten for a class, .Net automaically implements the +=, -=, *= and /= operators and the **DComplex** class does not explicitly override them.

Equality Operators

Two complex numbers are equal if the real parts of the two numbers are equal, and the imaginary parts of the two numbers are equal.

```
public static DComplex operator==
```

```
[C#]
DComplex c1 = new DComplex(1.0, 2.0);
DComplex c2 = new DComplex(3.0, 4.0);
if (c1 == c2) // not true based on the values above
{
}

[VB]
Dim c1 As New DComplex(1.0, 2.0)
Dim c2 As New DComplex(1.0, 2.0)
If c1 = c2 Then ' not true based on the values above

End If
```

```
public static DComplex operator!=
```

```
[C#]
DComplex c1 = new DComplex(1.0, 2.0);
DComplex c2 = new DComplex(3.0, 4.0);
if (c1 != c2)  // true based on the values above
{
}

[VB]
Dim c1 As New DComplex(1.0, 2.0)
Dim c2 As New DComplex(3.0, 4.0)
If c1 <> c2 Then ' true based on the values above

End If
```

The other equality operators <, <=, >, and >= are not applicable to complex numbers. That is because you cannot compare two complex numbers and decide if one is greater

than the other. For example, which is the larger number (100 + 5i), (5 + 100i), (5 – 100i), (100 – 5i). At best you can only compare the magnitudes of complex numbers. In that case, the complex numbers in the previous example are all equal, but fail the equality test ==. If you find you need to do some sort of greater than or less than test on two complex numbers, it is up to you to decide whether you look at: the real parts, the complex parts, or the magnitude of the complex number.

Complex Math Functions

The **DComplex** class also include many functions that need to be explicity calculated for complex numbers. These include the complex conjugate, magnitude (same as absolute value and modulus), normalization, polar angle, square root, raise to a power, and exponent.(e to a complex number). Each function comes in two forms: the first is a static function that operates on an argument that is an instance of a **DComplex** class. The second is a **DComplex** member function that operates on its own instance variables.

DComplex.Conj Method

The **complex conjugate** of the complex number $z = a + bi$ is defined to be $a - bi$

Get the conjugate of a complex number

```
public DComplex Conj();

public static DComplex Conj(DComplex);
```

```
[C#]
DComplex c1 = new DComplex(1.0, 2.0);
DComplex c2 = c1.Conj();
DComplex c3 = DComplex.Conj(c1);

[VB]
Dim c1 As New DComplex(1.0, 2.0)
Dim c2 As DComplex = c1.Conj()
Dim c3 As DComplex = DComplex.Conj(c1)
```

The complex conjugate of c1 is (1.0 – 2.0i).

DComplex.Abs Method

The **absolute value** (or *modulus* or *magnitude*) z of a complex number (a + bi) is $|z| = \sqrt{a^2 + b^2}$.

Calculate the absolute value of a complex number

```
public DComplex Abs ();

public static DComplex Abs (DComplex);
```

```
[C#]
DComplex c1 = new DComplex(3.0, 4.0);
double  r1 = c1.Abs();
double  r2 = DComplex.Abs(c1);


[VB]
Dim c1 As New DComplex(3.0, 4.0)
Dim r1 As Double = c1.Abs()
Dim r2 As Double = DComplex.Abs(c1)
```

The absolute value of c1 is a real number: DComplex.Abs(3 + 4i) = 5.

DComplex.Normalize Method

The normalize method scales the complex number so that it has a magnitude of 1. The normalized value z of the complex number (a + bi) is ((a/Magnitude(a + bi) + b/Magnitude(a + bi) i.

```
public DComplex Normalize ();

public static DComplex Normalize (DComplex);
```

```
[C#]
DComplex c1 = new DComplex(3.0, 4.0);
DComplex c2 = c1.Normalize();
DComplex c3 = DComplex.Normalize(c1);


[VB]
Dim c1 As New DComplex(3.0, 4.0)
Dim c2 As DComplex = c1.Normalize()
Dim c3 As DComplex = DComplex.Normalize(c1)
```

The normalized value of c1 is: (3.0/5 + 4.0/5 i) = (0.6 + 0.8i)

DComplex.PolarAngle Method

The **polar angle** r , in radians, of a complex number (a + bi) is:

r = Math.Atan2(b,a)

Calculate the polar angle of a complex number.

```
public DComplex PolarAngle ();

public static DComplex PolarAngle (DComplex);
```

```
[C#]
DComplex c1 = new DComplex(3.0, 4.0);
double r1 = c1.GetPolarAngle();
double r2 = DComplex.GetPolarAngle (c1);

[VB]
Dim c1 As New DComplex(3.0, 4.0)
Dim r1 As Double = c1.GetPolarAngle()
Dim r2 As Double = DComplex.GetPolarAngle(c1)
```

The polar angle of c1 is: Math.Atan2(4.0, 3.0) = .9273 radians

DComplex.Sqrt Method

Calculate the square root of a complex number.

```
public DComplex Sqrt ();

public static DComplex Sqrt (DComplex);
```

```
[C#]
DComplex c1 = new DComplex(3.0, 4.0);
DComplex c2 = c1.Sqrt ();
DComplex c3 = DComplex.Sqrt (c1);
```

```
[VB]
Dim c1 As New DComplex(3.0, 4.0)
Dim c2 As DComplex = c1.Sqrt()
Dim c3 As DComplex = DComplex.Sqrt(c1)
```

The square root of c1 is: (1.0 + 2.0i)

DComplex.Pow Method

Raise a complex number to real power.

```
public DComplex Pow (double);

public static DComplex Pow (DComplex, double);
```

```
[C#]
double r1 = 2.0;
DComplex c1 = new DComplex(3.0, 4.0);
DComplex c2 = c1.Pow(r1);
DComplex c3 = DComplex.Pow (c1, r1);

[VB]
Dim r1 As Double = 2.0
Dim c1 As New DComplex(3.0, 4.0)
Dim c2 As DComplex = c1.Pow(r1)
Dim c3 As DComplex = DComplex.Pow(c1, r1)
```

The value of $c1^2$ is: (-7.0 + 24.0i)

DComplex.Exp Method

Raise the value e to a complex power.

```
public DComplex Exp ();

public static DComplex Exp (DComplex);

[C#]
```

```
DComplex c1 = new DComplex(3.0, 4.0);
DComplex c2 = c1.Exp();
DComplex c3 = DComplex.Exp(c1);

[VB]
Dim c1 As New DComplex(3.0, 4.0)
Dim c2 As DComplex = c1.Exp()
Dim c3 As DComplex = DComplex.Exp(c1)
```

The value of e^{c1} is: (-13.128783081462162 - 15.200784463067956 i)

Miscellaneous Functions

The **DComplex** class also some support functions which make the input and output of complex numbers easier: ToString and Parse.

DComplex.ToString Method

This method converts the current value of the member variables into a string of the form "a + bi". The complex number (1.1 + 2.2i) is represented in string notation as "(1.1 + 2.2i)". The default numeric format of the two double values in the string are controlled by the "G" numeric format option of the double.ToString(string) format method. A second ToString method is supplied that can take the floating point format string as an argument.

Get the string representation of a complex number.

```
public override string ToString();

public string ToString(string);
```

DComplex.Parse Method

This method converts a string in the format "a + bi" into a **DComplex** object.

Get the string representation of a complex number.

```
public static DComplex Parse(string);
```

4. Matrix Classes (DDMat and DXMat classes)

MatBase
- **DMatBase**
  - **DDMat**
- **XMatBase**
  - **DXMat**

There are two matrix classes you will use for the input and output of numeric data to the linear algebra, linear systems, eigenvalue/eigenvector, and FFT algorithms: **DDMat** for real matrices and **DXMat** for complex matrices. Using the matrix classes you can read and write to individual elements; add, delete, swap, copy, scale, read/write rows and columns of a matrix. The matrix classes also carry out fundamental linear algebra subroutines such as vector and matrix norms, dot products and saxpy operations. Matrices can be initialized an element at a time, from standard .Net one-and two-dimensional double arrays (double [] and double [,]), from other matrices, and from files. The matrix classes also include operator overloads (+, -, *, /) that permit matrix math expressions of the type X = (A + B * C)/D, where X, A, B, C and D are matrix objects that follow the rules of matrix math, i.e. you do have to get the rows and column orders right. The matrix classes also double as vector classes, a matrix with a column or row dimension of one is considered a column or row vector respectively. In that case matrix elements can be accesses using 1-D vector brackets [], instead of the normal 2D matrix brackets [,].

Special note: Visual Basic in Visual Studio 2002 and Visual Studio 2003 do not have the ability to process overloaded operators. This feature is only supported under VB with Visual Studio 2005 and higher. Overloaded operators work with all versions of C#.

The **MatBase**, **DMatBase** and **XMatBase** classes are the base classes of the **DDMat** and **DXMat** classes. See the hierarchy at beginning of the chapter. Since these classes are abstract they can not be instantiated. They do contain important static and instance properties and methods used in the derived **DDMat** and **DXMat** classes. The only matrix classes you need to know how to instantiate are these two classes.

The **DDMat** and **DXMat** classes are very symmetrical. The methods and properties of the two classes all have the same names to make converting from one to the other as simple as possible. The major difference between the two classes is that the **DDMat** generally uses *double* arguments and the **DXMat** generally uses complex (class **DComplex**) arguments. This rule is not absolute, since some complex matrix functions do use double arguments and return double values. Because of the symmetry between the two matrix classes, constructors and methods will be documented in parallel to save space.

Linear Algebra Terminology

Matrices and linear algebra use mathematical terms not in common use with the average programmer. In order to qualify the special characteristics of different types of matrices, we use many of these terms.

Matrix order – The order of a matrix is the dimensions of the matrix, i.e. the number of rows and columns it has. Two matrices are of the same order if they have the same dimensions. The number of rows in a matrix is usually referred to using the letter *m*, the number of columns the letter *n*.

Transpose – The transpose of a real matrix is formed by taking an (m x n) matrix and converting it to an (n x m) matrix, making the rows of the original matrix the columns of the transposed matrix. For example, the row elements of the original matrix [0,0], [0,1], [0,2], …[0, n-1] become the column elements of the transposed matrix [0,0], [1,0], [2,0], …[n-1,0].

While it is possible to transpose a complex matrix using the simple description above, it is not mathematically correct. The proper mathematical transpose of a complex matrix is more properly called the conjugate transpose. In a conjugate transpose, the complex conjugate of the source row values become the new column values of the destination matrix. For example, if element [5,3] of the source matrix has the complex value (7 + 2i), the element [3,5] of the transposed matrix will have the value (7 – 2i), the complex conjugate of the original value.

Symmetric Matrix – A real matrix is considered to be symmetrical if it is square, and the elements above the diagonal are the mirror image of the elements below the diagonal, i.e. A[i,j] = A[j,i]. For example, in a symmetric matrix, the following element pairs, one above the diagonal and the other below the diagonal, must be equal: [5,3] = [3,5], [4,1] = [1,4], [11,7] = [7, 11],

While a complex matrix can be symmetric, A[i,j] = A[j,i], it is not a useful condition. Like the complex transpose, a mathematically symmetric complex matrix uses the complex conjugate. A truly symmetric complex matrix, known as a **Hermitian matrix**, requires that A[i,j] = Conjugate(A[j,i]). Using this definition, the diagonal values of a Hermitian matrix must be real (no imaginary component), since that is the only way a diagonal element can equal its own complex conjugate.

Positive Definite Matrix – a positive definite matrix is a **Symmetric (or Hermitian** for complex numbers**)** matrix that has the added property that all of its eigenvalues are positive. While it seems of little importance for the non-mathematician, the positive definite matrix shows up automatically in many linear algebra applications, including the solution of least squares problems (multiple regression) and the solution of coupled differential equations. Algorithms, Cholesky factorization in particular, have been developed explicitly to exploit the structure of positive definite matrices and these algorithms can be 2-4 times as fast as algorithms that work on more generalized matrices.

Orthogonal Matrix - an orthogonal matrix is a square matrix Q whose transpose is its inverse: $Q^T Q = QQ^T = I.$

Base-0 vs. Base-1 Matrices – Originally, most computer matrix math and linear algebra algorithms were written in FORTRAN and ALGOL. Those computer languages define the index range of their built in array types, dimension [m x n], as extending from [1..m, 1..n]. Matrices of this type use base-1 indexing. In contrast, C, C++, and C# all use base-0 indexing, where the index range of an array with the dimensions [m x n] is [0..m-1, 0..n-1]. Algorithms written for base-1 indexing will not work, and will generally crash programs written using compilers that require base-0 indexing.

This software assumes base-0 indexing. All matrices dimensioned to the size (m x n) use array indexing in the range [0..m-1, 0..n-1]. The software includes routines that will convert a base-0 matrix into a base-1 matrix. In that case, the base-0 matrix dimensioned to size (m x n), with array indexing of [0..m-1, 0..n-1], is converted to a matrix size (m + 1) x (n + 1) that can be used with 1-based indexing in the range [1..m, 1..n]. All of the data in the original matrix is shifted one column and one row so that all data fits in the new index range of [1..m, 1..n]. While the 0 row and column indices in these converted matrices are still useable, in a true base-1 algorithm, they would never be accessed, because they are considered out of range. A base-1 matrix can be converted back to a base-0 matrix. In that case the base-1 matrix, dimension (m + 1) x (n + 1) is converted back to a matrix of with the dimensions (m x n). The data is shifted back one row and one column, so that the data starts in the 0^{th} row and column.

Matrix Constructors

Define a matrix with the dimensions (*rows* x *columns*).

DDMat

```
[VB]    Public Sub New( ByVal rows As Integer, ByVal columns As Integer )
[C#]    public DDMat( int rows,  int columns);
```

DXMat

```
[VB]    Public Sub New( ByVal rows As Integer, ByVal columns As Integer )
[C#]    public DXMat( int rows,  int columns);
```

Construct a matrix as a copy of the *source* matrix.

DDMat

```
[VB]    Public Sub New(ByVal source As DDMat )
[C#]    public DDMat( DDMat source);
```

DXMat

```
[VB]    Public Sub New(ByVal source As DXMat )
[C#]    public DXMat( DXMat source);
```

Construct vector as the column or row (*rcflag* = V_ROW or VCOL) of the source matrix. The index of the column or row to copy is *rcnum*.

DDMat

```
[VB] Public Sub New(ByVal source As DDMat,
                    ByVal rcflag As Integer,
                    ByVal rcnum As Integer)
[C#] public DDMat(DDMat source, int rcflag, int rcnum);
```

DXMat

```
[VB] Public Sub New(ByVal source As DXMat,
                    ByVal rcflag As Integer,
                    ByVal rcnum As Integer)
[C#] public DXMat(DXMat source, int rcflag, int rcnum);
```

Construct a matrix with the dimension (*rows* x *columns)* and initialize it with triplets from the *trips* array.

DDMat

```
[VB]    Public Sub New(ByVal trips As DTriplet(),
                       ByVal rows As Integer,
                       ByVal columns As Integer )
[C#]    public DDMat( DTriplet[] trips, int rows, int columns);
```

DXMat

```
[VB]    Public Sub New(ByVal trips As XTriplet(),
                       ByVal rows As Integer,
                       ByVal columns As Integer )
[C#]    public DXMat ( XTriplet[] trips, int rows, int columns);
```

Construct a vector initialized using the 1D *source* array. The **DXMat** matrix has a constructor the initializes the real and imaginary parts of a complex matrix using the *resource* and *imsource* .Net 1D arrays.

DDMat

```
[VB]    Public Sub New(ByVal source As Double() )
[C#]    public DDMat( double[] source);
```

DXMat

```
[VB] Public Sub New(ByVal source As DComplex() )
[C#] public DXMat(DComplex [] source);

[VB] Public Sub New(ByVal resource As Double(), ByVal imsource As Double())
[C#] public DXMat(double[] resource, double[] imsource);
```

Construct a matrix using the *source* .Net 2D array. The **DXMat** matrix has a constructor the initializes the real and imaginary parts of a complex matrix using the *resource* and *imsource* .Net 2D arrays.

DDMat

```
[VB] Public Sub New(ByVal source As Double(,) )
[C#] public DDMat(double[,] source);
```

DXMat

```
[VB] Public Sub New(ByVal source  As DComplex(,) )
[C#] public DXMat(DComplex[,] resource);

[VB] Public Sub New(ByVal resource As Double(,), ByVal imsource As Double(,))
[C#] public DXMat(double[,] resource, double[,] imsource);
```

Construct a matrix as a vector with the dimension *elements*.

DDMat

```
[VB]    Public Sub New(  ByVal elements As Integer )
[C#]    public DDMat( int elements);
```

DXMat

```
[VB]    Public Sub New(  ByVal elements As Integer )
[C#]    public DXMat( int elements);
```

Construct a matrix as a vector, dimension *elements*, and initialize all elements to the value *r*.

DDMat

```
[VB]    Public Sub New(ByVal elements As Integer,  ByVal r As Double )
[C#]    public DDMat( int elements, double r);
```

```
DXMat
[VB]    Public Sub New(ByVal elements As Integer,  ByVal r As DComplex )
[C#]    public DXMat( int elements, DComplex r);
```

Matrix Operators

Matrices are added, subtracted, multiplied, and divided following the rules of linear algebra. Since the standard .Net arithmetic operators (+, -, *, /) do not automatically work with user defined classes, the **DDMat** and **DXMat** classes override these operators so that you can use a mix of matrix and double values in math expressions.

Special note: Visual Basic in Visual Studio 2002 and Visual Studio 2003 do not have the ability to process overloaded operators. This feature is only supported under VB with Visual Studio 2005 and higher. Overloaded operators work with all versions of C#. There are function equivalents to every operator overload (Negate, Add, Subtract, Multiple, Divide, Equals) that can be used with all .Net versions of VB.

Matrix Addition

```
public static DDMat operator+
public static DXMat operator+
```

Two or more matrices of identical dimensions *m* and *n* can be added. Given *m*-by-*n* matrices *A* and *B*, their **sum** *A* + *B* is the *m*-by-*n* matrix computed by adding corresponding matrix elements.

```
[C#]
double [,] aData = {{1,2,3}, {4,5,6}, {7,8,9}};
double [,] bData = {{5,6,7}, {9,7,8}, {3,2,1}};
DDMat A = new DDMat(aData);
DDMat B = new DDMat(bData);
DDMat C = A + B;

[VB]
Dim aData As Double(,) = {{1, 2, 3}, {4, 5, 6}, {7, 8, 9}}
Dim bData As Double(,) = {{5, 6, 7}, {9, 7, 8}, {3, 2, 1}}
Dim A As New DDMat(aData)
Dim B As New DDMat(bData)
'  Dim C As DDMat = A + B  ' VB 2005 and greater only
Dim C As DDMat = DDMat.Add(A, B)
```

Matrix Subtraction

```
public static DDMat operator-
public static DXMat operator-
```

Two or more matrices of identical dimensions *m* and *n* can be subtracted. Given *m*-by-*n* matrices *A* and *B*, their **difference** *A* - *B* is the *m*-by-*n* matrix computed by subtracting corresponding matrix elements.

```
[C#]
double [,] aData = {{1,2,3}, {4,5,6}, {7,8,9}};
double [,] bData = {{5,6,7}, {9,7,8}, {3,2,1}};
DDMat A = new DDMat(aData);
DDMat B = new DDMat(bData);
DDMat C = A - B;


[VB]
Dim aData As Double(,) = {{1, 2, 3}, {4, 5, 6}, {7, 8, 9}}
Dim bData As Double(,) = {{5, 6, 7}, {9, 7, 8}, {3, 2, 1}}
Dim A As New DDMat(aData)
Dim B As New DDMat(bData)
'   Dim C As DDMat = A - B  '  VB 2005 and greater only
Dim C As DDMat = DDMat.Subtraction(A, B)
```

Matrix Multiplication

```
public static DDMat operator*
public static DXMat operator*
```

Two or more matrices of proper dimenson can be multiplied. The number of columns of the left matrix must be the same as the number of rows of the right matrix. Given a matrix A (*m* x *n)* and a matrix B (n x p), the size of the matrix C, that is the product of A * B = C, is (m x p).

```
[C#]
double [,] aData = {{1,2,3,4},{4,5,6,7},{7,8,9, 10}}; // (3 x 4)
double [,] bData = {{5,6,7,8,9},{9,7,8,6,4},{3,2,1,0,9},{3,7,0,4,7}}; // (4 x 5)
DDMat A = new DDMat(aData);
DDMat B = new DDMat(bData);
DDMat C = A * B; // (3 x 5)


[VB]
Dim aData As Double(,) = {{1, 2, 3, 4}, {4, 5, 6, 7}, {7, 8, 9, 10}} ' (3 x 4)
Dim bData As Double(,) = {{5, 6, 7, 8, 9}, {9, 7, 8, 6, 4}, {3, 2, 1, 0, 9}, {3,
7, 0, 4, 7}} ' (4 x 5)
Dim A As New DDMat(aData)
Dim B As New DDMat(bData)
'    Dim C As DDMat = A * B ' (3 x 5) VB 2005 and greater only
Dim C As DDMat = DDMat.Multiply(A, B) ' (3 x 5)
```

Scalar Multiplication

```
public static DDMat operator*
```

```
public static DXMat operator*
```

Given a matrix A, and a scalar c, the product of A * c is calculated by multiplying every element of the matrix A by the scalar c.

```
[C#]
double [,] aData = {{1,2,3,4},{4,5,6,7},{7,8,9, 10}}; // (3 x 4)
DDMat A = new DDMat(aData);
double c = 3.1415;
DDMat B = A * c;

[VB]
Dim aData As Double(,) = {{1, 2, 3, 4}, {4, 5, 6, 7}, {7, 8, 9, 10}}  ' (3 x 4)
Dim A As New DDMat(aData)
Dim c As Double = 3.1415
' Dim B As DDMat = A * c    ' VB 2005 and greater only
Dim B As DDMat = DDMat.Multiply(A, c)
```

Matrix Multiplication

```
public static DDMat operator*
public static DXMat operator*
```

Two or more matrices of proper dimenson can be multiplied. The number of columns of the left matrix must be the same as the number of rows of the right matrix. Given a matrix A (*m* x *n)* and a matrix B (n x p), the size of the matrix C, that is the product of A * B = C, is (m x p).

```
[C#]
double [,] aData = {{1,2,3,4},{4,5,6,7},{7,8,9, 10}}; // (3 x 4)
double [,] bData = {{5,6,7,8,9},{9,7,8,6,4},{3,2,1,0,9},{3,7,0,4,7}}; // (4 x 5)
DDMat A = new DDMat(aData);
DDMat B = new DDMat(bData);
DDMat C = A * B; // (3 x 5)

[VB]
Dim aData As Double(,) = {{1, 2, 3, 4}, {4, 5, 6, 7}, {7, 8, 9, 10}}  ' (3 x 4)
Dim bData As Double(,) = {{5, 6, 7, 8, 9}, {9, 7, 8, 6, 4}, {3, 2, 1, 0, 9}, {3,
7, 0, 4, 7}}
Dim A As New DDMat(aData)
Dim B As New DDMat(bData)
'  Dim C As DDMat = A * B ' (3 x 5) VB 2005 and greater only
Dim C As DDMat = DDMat.Multiply(A, B) ' (3 x 5)
```

Matrix Division

```
public static DDMat operator/
```

```
public static DXMat operator/
```

Matrix division is a bit of a misnomer, since the divide sign doesn't often appear in linear algebra forumlas. Take the the matrix expression b/A. This can be rewritten as $x = b*A^{-1}$, where A^{-1} is the matrix inverse of A. In general, you never want to solve for a matrix inverse, then use that inverse in subsequent calculations. It is not as accurate, nor as fast as alternative methods. When this software sees a divide sign in a matrix expression, it redefines the original problem x = b/A as the matrix expression Ax = b, which is the standard format for solving for system of linear equations, solves for x, then replaces the expression b/A with the matrix x. In order for this to work properly, A must be square and the number of rows in b must equal the number of columns in A.

```
[C#]
double [,] aData = {{1,2,3,4},{4,5,6,7},{7,8,9, 10} ,{10,1,5,7}}; // (4 x 4)
double [,] bData = {{5},{6},{7},{8}}; // (4 x 1)
DDMat A = new DDMat(aData);
DDMat B = new DDMat(bData);
DDMat C = A / B;

[VB]
Dim aData As Double(,) = {{1, 2, 3, 4}, {4, 5, 6, 7}, {7, 8, 9, 10}, {10, 1, 5,
7}} ' (4 x 4)
Dim bData As Double(,) = {{5}, {6}, {7}, {8}}  ' (4 x 1)
Dim A As New DDMat(aData)
Dim B As New DDMat(bData)
' Dim C As DDMat = A / B 'VB 2005 and greater only
Dim C As DDMat = DDMat.Divide(A, B)
```

Scalar Division

```
public static DDMat operator/
public static DXMat operator/
```

Given a matrix A, and a scalar c, the division of A / c is calculated by dividing every element of the matrix A by the scalar c.

```
[C#]
double [,] aData = {{1,2,3,4},{4,5,6,7},{7,8,9, 10}}; // (3 x 4)
DDMat A = new DDMat(aData);
double c = 3.1415;
DDMat B = A / c;

[VB]
Dim aData As Double(,) = {{1, 2, 3, 4}, {4, 5, 6, 7}, {7, 8, 9, 10}}  ' (3 x 4)
Dim A As New DDMat(aData)
Dim c As Double = 3.1415
' Dim B As DDMat = A / c 'VB 2005 and greater only
```

```
Dim B As DDMat = DDMat.Divide(A, c)
```

Mix all of the operators in complex math expressions

```
[C#]
double [,] aData = {{1,2,3,4},{4,5,6,7},{7,8,9, 10}}; // (3 x 4)
double [,] bData = {{5,6,7,8,9},{9,7,8,6,4},{3,2,1,0,9},{3,7,0,4,7}}; // (4 x 5)
double [,] cData = {{5,6,7,8,9},{9,7,8,6,4},{3,2,1,0,9}}; // (3 x 5)

DDMat A = new DDMat(aData);
DDMat B = new DDMat(bData);
DDMat C = new DDMat(cData);

DDMat D = A * B + C * 3.1415; // (3 x 5)

[VB]
Dim aData As Double(,) = {{1, 2, 3, 4}, {4, 5, 6, 7}, {7, 8, 9, 10}}  ' (3 x 4)
Dim bData As Double(,) = {{5, 6, 7, 8, 9}, {9, 7, 8, 6, 4}, {3, 2, 1, 0, 9}, {3,
7, 0, 4, 7}}  ' (4 x 5)
Dim cData As Double(,) = {{5, 6, 7, 8, 9}, {9, 7, 8, 6, 4}, {3, 2, 1, 0, 9}}  '3 x
5
Dim A As New DDMat(aData)
Dim B As New DDMat(bData)
Dim C As New DDMat(cData)

'   Dim D As DDMat = A * B + C * 3.1415 ' (3 x 5) VB 2005 and greater only
Dim D As DDMat = DDMat.Add(DDMat.Multiply(A, B), DDMat.Multiply(C, 3.1415))
```

Once the +, -, * and / operators are overwritten for a class, .Net automaically implements the +=, -=, *= and /= operators and the **DDMat** class does not explicitly override them.

Matrix Methods

Many methods are available in the **DDMat** and **DXMat** classes that manipulate the rows and columns of the matrix. Other methods calculate important characteristics of the matrix. Since the **DDMat** and **DXMat** classes include the same routines they are documented in parallel. A subset of the available methods follows. A complete description is found in the XXXXX help file.

Method DDMat.C, DXMat.C

Returns the specified column, or a sub range of the column, as a vector

DDMat

```
[VB]  Function C( ByVal col As Integer ) As DDMat
[C#]  DDMat C(int col);

[VB]  Function C(ByVal col As Integer,
                 ByVal start As Integer,
                 ByVal num As Integer
                 ) As DDMat
[C#]  DDMat C(int col, int start, int num);
```

DXMat

```
[VB]  Function C( ByVal col As Integer ) As DXMat
[C#]  DXMat C(int col);

[VB]  Function C(ByVal col As Integer,
                 ByVal start As Integer,
                 ByVal num As Integer
                 ) As DXMat
[C#]  DXMat C(int col, int start, int num);
```

Parameters

col specified column
start specified row to start copying from
start number to copy

Return Value

Returns the specified column, or a sub range of the column, as a vector

Method DDMat.Clone, DXMat.Clone

Returns an object that is a clone of this array object.

DDMat

```
[VB]  Function Clone() As Object Implements ICloneable.Clone
[C#]  object Clone();
```

DXMat

```
[VB]  Function Clone() As Object Implements ICloneable.Clone
```

```
[C#]  object Clone();
```

Return Value

Returns a clone of this matrix object.

Implements

ICloneable.Clone

Method DDMat.Copy, DXMat.Copy

Copy a matrix.

DDMat

```
[VB]  Sub Copy(ByVal src As DMatBase)
[C#]  void Copy(DMatBase src);
```

DXMat

```
[VB]  Sub Copy(ByVal src As XMatBase)
[C#]  void Copy(XMatBase src);
```

Parameters

src source array

Method DDMat.Determinant, DXMat.Determinant, DDMat.D, DXMat.D

Returns the determinant of the current matrix.

DDMat

```
[VB]  Function Determinant() As Double
[C#]  double Determinant();

[VB]  Function D() As double
[C#]  double D();
```

DXMat

```
[VB]  Function Determinant() As DComplex
[C#]  DComplex Determinant();

[VB]  Function D() As DComplex
[C#]  DComplex D();
```

Return Value

Returns the determinant.

Method DDMat. Equals, DXMat.Equals

Equals comparator. Two matrices are considered equal if they are the same dimension and if each corresponding element at matrix index [i,j] is equal.

DDMat

```
[VB]  Function Equals( ByVal obj As DDMat) As Boolean
[C#]  bool Equals(DDMat obj);
```

DXMat

```
[VB]  Function Equals( ByVal obj As DXMat) As Boolean
[C#]  bool Equals(DXMat obj);
```

Parameters

obj Returns true if the source object is equal to the current object.

Return Value

Returns true if the source object is equal to the current object.

Method DDMat.GetDataBuffer, DXMat.GetDataBuffer

Returns a reference to the internal **DComplex** [,] data buffer that stores the matrix data.

DDMat

```
[VB]  Function GetDataBuffer() As Double (,)
[C#]  double[,] GetDataBuffer();
```

DXMat

```
[VB]  Function GetDataBuffer() As DComplex(,)
[C#]  DComplex[,] GetDataBuffer();
```

Return Value

Returns a reference to the internal matrix buffer.

Method DDMat.GetDiagonal, DXMat.GetDiagonal

Returns a vector that is the diagonal of the matrix.

DDMat

```
[VB]  Function GetDiagonal() As DDMat
[C#]  DDMat GetDiagonal();
```

DXMat

```
[VB]  Function GetDiagonal() As DXMat
[C#]  DXMat GetDiagonal();
```

Return Value

Returns a vector that is the diagonal of the matrix.

Method DDMat.GetElement, DXMat.GetElement

Returns the element of the matrix.

DDMat

```
[VB]  Function GetElement( ByVal row As Integer,
         ByVal column As Integer) As Double
[C#]  double GetElement( int row, int column);
```

DXMat

```
[VB]  Function GetElement( ByVal row As Integer,
         ByVal column As Integer) As DComplex
[C#]  DComplex GetElement( int row, int column);
```

Parameters

row The row of the matrix element.
column The column of the matrix element.

Return Value

Returns the value of the matrix element.

Method DDMat.GetMatrix, DXMat.GetMatrix

Initialize an external matrix to match this one.

DDMat

```
[VB]  Sub GetMatrix( ByVal dest As DDMat )
[C#]  void GetMatrix( DDMat dest);
```

DXMat

```
[VB]  Sub GetMatrix( ByVal dest As DXMat )
[C#]  void GetMatrix( DXMat dest);
```

Parameters

dest destination array

Method DDMat.GetTranspose, DXMat.GetTranspose

Returns the transpose of a matrix. A complex transpose converts the complex numbers to their complex conjugate: i.e, a + bi -> a - bi.

DXMat

```
[VB]  GetTranspose() As DDMat
[C#]  DDMat GetTranspose();
```

DXMat

```
[VB]  GetTranspose() As DXMat
[C#]  DXMat GetTranspose();
```

Return Value

Returns the transpose of the matrix.

Method DDMat.GetVector, DXMat.GetVector

Returns a [] vector of the data in the matrix.

DDMat

```
[VB]  Function GetVector() As Double()
[C#]  double[] GetVector();
```

DXMat

```
[VB]  Function GetVector() As DComplex()
[C#]  DComplex[] GetVector();
```

Return Value

Returns a [] vector of the data in the matrix.

Method DDMat.GetVectorElement, DXMat.GetVectorElement

Set an element of a vector.

DDMat

```
[VB] Function GetVectorElement(
      ByVal element As Integer) As Double
[C#] double GetVectorElement(int element);
```

DXMat

```
[VB] Function GetVectorElement(
      ByVal element As Integer) As DComplex
[C#] DComplex GetVectorElement(int element);
```

Parameters

element The index of the vector element.

Return Value

The value of the vector element.

Method DDMat.I, DXMat.I

Returns the inversion of the current matrix.

DDMat

```
[VB]  Function I() As DDMat
[C#]  DDMat I();
```

DXMat

```
[VB]  Function I() As DXMat
[C#]  DXMat I();
```

Return Value

Returns the inversion of the current matrix.

Method DDMat.Invert, DXMat.Invert

Returns the inversion of the specified matrix.

DDMat

```
[VB] Shared Function Invert(ByVal A As DDMat ) As Integer
[C#] static int Invert( DDMat A);
```

DXMat

```
[VB] Shared Function Invert(ByVal A As DXMat ) As Integer
[C#] static int Invert( DXMat A);
```

Parameters

A Returns the inversion of the matrix, overwriting the original matrix.

Return Value

Returns an error code. See the **MatError** class error code list.

Method DDMat.MakeRandomLEq, DXMat.MakeRandomLEq

Make a pair of matrices that form the A and b matrices of a linear set of equations, Ax = b. The matrices are constructed so that the solution (x) of Ax = b is always a vector with the values [1, 2, 3, ..., rank].

DDMat

```
[VB]  Shared Sub MakeRandomLEq( ByVal A As DDMat,
         ByVal b As DDMat,
         ByVal rank As Integer,
         ByVal posdefsym As Boolean)


[C#]  static void MakeRandomLEq(
                DDMatA,
                DDMatb,
                int rank,
                bool posdefsym);
```

DXMat

```
[VB]  Shared Sub MakeRandomLEq( ByVal A As DXMat,
         ByVal b As DXMat,
         ByVal rank As Integer,
         ByVal posdefsym As Boolean)


[C#]  static void MakeRandomLEq(
                DXMat A,
                DXMat b,
                int rank,
                bool posdefsym);
```

Parameters

A	Returns the coefficient array, A, of the linear system of equations.
b	Returns the right hand side array, b, of the linear system of equations.
rank	The number of rows and columns of the coefficient A matrix.
posdefsym	Set to true and the A matrix will be symmetric (hermitian)-positive-definite

Method DDMat.MakeRandomMatrix, DXMat.MakeRandomMatrix

Make a random, square, matrix of the specified rank and symmetry.

DDMat

```
[VB]  Shared Function MakeRandomMatrix(
         ByVal rank As Integer,
         ByVal posdefsym As Boolean ) As DDMat

[C#]  static DDMat MakeRandomMatrix(
         int rank,
         bool posdefsym);
```

DXMat

```
[VB]   Shared Function MakeRandomMatrix(
          ByVal rank As Integer,
          ByVal posdefsym As Boolean ) As DXMat
[C#]   static DXMat MakeRandomMatrix(
          int rank,
          bool posdefsym);
```

Parameters

rank The number of rows and columns of the generated matrix.
posdefsym Set to true and the A matrix will be symmetric (hermitian for complex) - positive-definite

Return Value

Returns the new matrix.

Method DDMat.MakeRHSFromCoefs, DXMat.MakeRHSFromCoefs

Using the coefficient matrix A, a rhs vector (b) is constructed so that the solution x, of the linear system of equations Ax = b is [1, 2, 3, ..., rank]

DDMat

```
[VB]   Shared Function MakeRHSFromCoefs(
                ByVal A As DDMat ) As DDMat
[C#]   static DDMat MakeRHSFromCoefs(DDMat A);
```

DXMat

```
[VB]   Shared Function MakeRHSFromCoefs(
                ByVal A As DXMat ) As DXMat
[C#]   static DXMat MakeRHSFromCoefs(DXMat A);
```

Parameters

A Returns the coefficient array, A, of the linear system of equations.

Return Value

Returns the rhs vector.

Method DDMat.Product, DXMat.Product

Calculates the product of two matrices (A * B) and returns the result as a third matrix.

DDMat

```
[VB]   Shared Function Product(
       ByVal A As DDMat,
       ByVal B As DDMat) As DDMat
[C#]   static DDMatProduct( DDMat A, DDMat B);
```

DXMat

```
[VB]   Shared Function Product(ByVal A As DXMat,
             ByVal B As DXMat ) As DXMat
[C#]   static DXMat Product( DXMat A, DXMat B);
```

Parameters

A The first of two arguments in the matrix multiple (A * B).
B The second of two arguments in the matrix multiple (A * B).

Return Value

Returns the product of two matrices (A * B).

Method DDMat.R, DXMat.R

Returns the specified row, or a sub range of the row, as a vector

DDMat

```
[VB]   Function C( ByVal row As Integer ) As DDMat
[C#]   DDMat C(int row);

[VB]   Function C(ByVal row As Integer,
                  ByVal start As Integer,
                  ByVal num As Integer ) As DDMat
[C#]   DDMat C(int row, int start, int num);
```

DXMat

```
[VB]   Function C( ByVal row As Integer ) As DXMat
[C#]   DXMat C(int row);

[VB]   Function C(ByVal row As Integer,
                  ByVal start As Integer,
                  ByVal num As Integer ) As DXMat
[C#]   DXMat C(int row, int start, int num);
```

Parameters

row specified column
start specified column to start copying from
start number to copy

Return Value

Returns the specified row, or a sub range of the row, as a vector

Method DDMat.SetElement, DXMat.SetElement

Set a matrix element.

DDMat

```
[VB]  Sub SetElement(
   ByVal row As Integer,
   ByVal column As Integer,
   ByVal value As Double
)


[C#]  void SetElement(
   int row,
   int column,
   double value);
```

DXMat

```
[VB]  Sub SetElement(
   ByVal row As Integer,
   ByVal column As Integer,
   ByVal value As DComplex
)


[C#]  void SetElement(
   int row,
   int column,
   DComplex value);
```

Parameters

row The row of the matrix element.
column The column of the matrix element.
value The value of the matrix element.

Method DDMat.SetMatrix, DXMat.SetMatrix

DDMat

```
[VB]  Sub SetMatrix(ByVal source As Double (,))
[C#]  void SetMatrix(double [,] source);

[VB]  Sub SetMatrix( ByVal source As DDMat )
[C#]  void SetMatrix(DDMat source);
```

DXMat

```
[VB]  Sub SetMatrix(ByVal source As DComplex(,))
[C#]  void SetMatrix(DComplex[,] source);

[VB]  Sub SetMatrix( ByVal source As DXMat )
[C#]  void SetMatrix(DXMat source);
```

Parameters

source source array

Method DDMat.T, DXMat.T

Returns the transpose of the current matrix. A complex transpose converts the complex numbers to their complex conjugate: i.e., a + bi -> a - bi.

DDMat

```
[VB] T() As DDMat
[C#] public DDMat T();
```

DXMat

```
[VB] T() As DXMat
[C#] public DXMat T();
```

Return Value

Returns the transpose of the current matrix.

Indexers: DMatBase.Item, XMatBase.Item

This property get/sets the value of an individual element in a matrix vector.

DDMat

```
[VB]  Default Property Item(  ByVal index As Integer) As Double
[C#]  double this[int index] {get; set;}
```

DXMat

```
[VB]  Default Property Item(  ByVal index As Integer) As DComplex
[C#]  DComplex this[int index] {get; set;}
```

Parameters

index The index of the matrix vector element.

This property get/sets the value of an individual element in a matrix.

DDMat

```
[VB]  Default Property Item(  ByVal index As Integer) As Double
[C#]  double this[int index] {get; set;}
```

DXMat

```
[VB]  Default Property Item(  ByVal row As Integer,
   ByVal column As Integer ) As DComplex
[C#] public virtual DComplex this[int row,int column] {get; set;}
```

Parameters

row The row index of the matrix element.
column The column index of the matrix element.

Method DDMat.DataBuffer, DXMat.DataBuffer

Returns a reference to the [,] array object that represents internal data buffer. This reference will remain valid only as long as the array is not forced to resize, forcing a reallocation of the internal buffer.

DDMat

```
[VB]  ReadOnly Property DataBuffer As Double(,)
[C#]  double[,] DataBuffer {get;}
```

DXMat

```
[VB]  ReadOnly Property DataBuffer As DComplex(,)
[C#]  DComplex[,] DataBuffer {get;}
```

Method DMatBase.Load, XMatBase.Load

These method will open a text file and read the CSV (Comma Separated Value) formatted data values in that file. A CSV file can be created by popular spreadsheet and word processing programs. Some localization for different operating systems and locales can be handled by the modifying the default *csv* (**MatCSV**) object. The file can be organized so that the columns represent groups and the rows represent data values for each group (COLUMN_MAJOR), or the where the rows represent groups and the columns represent data values for each group (ROW_MAJOR). Use the **MatCSV.SetOrientation** method to initialize the *csv* argument for the proper data orientation.

```
[VB]  Function Load(
   ByVal csv As MatCSV,
   ByVal filename As String,
   ByVal rowskip As Integer,
   ByVal columnskip As Integer
) As Integer


[C#]  int Load(
   MatCSV csv,
   string filename,
   int rowskip,
   int columnskip
);
```

Parameters

csv	An instance of a MatCSV object.
filename	The name of the file.
rowskip	Skip this many rows before starting the read operation
columnskip	For each new row, skip this many columns before starting read.

These methods will open a text file and read the CSV (Comma Separated Value) formatted data values in that file. A CSV file can be created by popular spreadsheet and word processing programs. This version of **Load** assumes CSV values are organized in a ROW_MAJOR format.

```
[VB]  Function Load(ByVal filename As String) As Integer
[C#]  int Load(string filename);
```

filename	The name of the file.

Method DMatBase.Save, XMatBase.Save

This method will create a text file and output the dataset to that file in a CSV (Comma Separated Value) format. A CSV file can be read by popular spreadsheet and word processing programs. Some localization for different operating systems and locales can be handled by the modifying the default *csv* (MatCSV) object. The file can be organized so that the columns represent groups and the rows represent data values for each group (COLUMN_MAJOR), or the where the rows represent groups and the columns represent data values for each group (ROW_MAJOR). Use the MatCSV.SetOrientation method to initialize the *csv* argument for the proper data orientation.

```
[VB] Function Save(ByVal csv As MatCSV,
         ByVal filename As String) As Integer
[C#] public int Save(MatCSV csv,string filename);


[VB] Public Function Save(
         ByVal csv As MatCSV, ByVal filename As String,
         ByVal append As Boolean) As Integer
[C#] public int Save(MatCSV csv, string filename, bool append);


[VB] Function Save(ByVal filename As String) As Integer
[C#] public int Save(string filename);
```

Parameters

csv	An instance of a MatCSV object.
filename	The name of the file.
append	True and if the file exists, data is appended to the file.

A Summary of all DDMat, DXMat Methods

Public Static (Shared) Methods

Determinant	Overloaded. Returns the inversion, and determinant of the specified matrix.
Invert	Returns the inversion of the specified matrix.
MakeRandomLEq	Make a pair of matrices that form the A and b matrices of a linear set of equations, Ax = b. The matrices are constructed so that the solution (x) of Ax = b is always a vector with the values [1, 2, 3, ...,rank].

MakeRandomMatrix	Make a random, square, matrix of the specified rank, symmetry and diagonal dominance.
MakeRHSFromCoefs	Using the coefficient matrix A, a rhs vector (b) is constructed so that the solution x, of the linear system of equations Ax = b is [1, 2, 3, ..., rank]
Product	Calculates the product of two matrices (A * B) and returns the result as a third matrix.

Public Static (Shared) Operators

Addition Operator	+ (matrix addition) operator overload
Division Operator	Overloaded. / operator overload solves the linear system of equations x = b/A, or more appropriately Ax = b.
Multiplication Operator	Overloaded. * (matrix * matrix) operator overload
Subtraction Operator	- (matrix subtraction) operator overload
Unary Negation Operator	- (matrix negation) operator overload

Public Instance Constructors

DDMat	Overloaded. Initializes a new instance of the DDMat class.

Public Instance Properties

DataBuffer	Returns a reference to the Array object that represents internal data buffer. This reference will remain valid only as long as the array is not forced to resize, forcing a reallocation of the internal buffer.
IsSquare	Returns true if the matrix is square (numRows == numColumns).
IsSymmetric	Returns true if the matrix is symmetric (A = Transpose(A)).
Item	Overloaded. This property get/sets the value of an individual element in a vector. The matrix vector index.
Length	Returns the number of rows * columns in the matrix.
NumColumns	Returns the number of columns in the matrix.
NumRows	Returns the number of rows in the matrix.

OK	Returns true if no error pending in matrix.

Public Instance Methods

AddConstCol	Add a constant to a column of the current matrix.
AddConstRow	Add a constant to a row of the current matrix.
C	Overloaded. Returns the specified column as a vector.
Cholesky_Solve	Solve a system of linear equations (using Cholesky Decomposition) in the standard form Ax = b, where A is the coefficient matrix, b is the right hand side and x is the solution. The A matrix must be symmetric positive-definite matrix. Cholesky is the fastest technique for solving linear systems of equations, though it does require the coefficient matrix be symmetric positive-definite.
Clone	Returns an object that is a clone of this matrix object.
CondNum	Calculate square matrix condition number
ConvertFromBaseOne	Convert the current matrix from a base one matrix to a base zero matrix.
ConvertToBaseOne	Convert a base zero matrix to a base one matrix.
Copy	Copy a matrix.
D	Returns the determinant of the current matrix.
DeleteCol	Delete a column from the current matrix, decreasing the column count of the matrix by one.
DeleteRow	Delete a row from the current matrix, decreasing the row count of the matrix by one.
Deter	Returns the determinant of the current matrix. Gauss-Jordan is used.
Determinant	Overloaded. Returns the determinant of the current matrix.
DimMatrix	Dimension the matrix for size [0..rows-1, 0..columns-1]
DimZero	Returns true if the matrix dimensioned to 0,0.

Equals	Overloaded. Determines whether the specified Object is equal to the current **Object**.
Equals	Overloaded. Determines whether the specified Object is equal to the current **Object**.
FreeMat	Initializes the matrix to empty, 0 rows and 0 columns.
FromDMatBase	Initializes the matrix from the source matrix.
FromTriplets	Initialize the matrix using an array of triplets (DTriplet). Elements not initialized remain at their default 0.0 value.
GetBaseOneMatrix	Return a copy of the current matrix as a base one array.
GetCol	Get a 1D array representing a copy of a column in this matrix.
GetCompatibleMatrix	Overloaded. Get a matrix compatible with this one, initialized with and dimensioned to the size of the source array.
GetDataBuffer	Returns a reference to the internal double [,] data buffer that stores the matrix data.
GetDiagonal	Overloaded. Get a vector representing a copy of the diagonal elements of this matrix.
GetDiagonal	Overloaded. Returns a vector that is the diagonal of this one.
GetElement	Returns the element of the matrix.
GetError	Return the current matrix error.
GetHashCode	Serves as a hash function for a particular type, suitable for use in hashing algorithms and data structures like a hash table.
GetLength	Returns the number of rows * columns in the matrix.
GetMatrix	Overloaded. Get a 2D array representing a copy of the values in this matrix.
GetMatrix	Overloaded. Initialize an external DDMat matrix to match this one.
GetNumNonZeroEl	Returns the number of non-zero elements in the matrix.
GetRC	Get a row or a column of the matrix.
GetRow	Get a row in the matrix.

GetSubCol	Get a sub range of a column in the matrix.
GetSubRC	Get a sub range of a row or a column in the matrix.
GetSubRow	Get a sub range of a row in the matrix.
GetTransp	Returns the transpose of the current matrix.
GetTranspose	Returns a matrix that is the transpose of this one.
GetTriplets	Get an array of triplets representing the non-zero elements of the matrix.
GetType	Gets the Type of the current instance.
GetVector	Returns a double [] vector of the data in the matrix.
GetVectorElement	Set an element of the vector.
GJ_Solve	Solve a system of linear equations (using Gauss-Jordan) in the standard form Ax = b, where A is the coefficient matrix, b is the right hand side and x is the solution. The A matrix must be symmetric positive-definite matrix. Gauss-Jordan with partial pivoting is a very stable method of solving systems of equations.
I	Returns the inversion of the current matrix.
Initialize	Initialize the entire matrix to the specified value.
InsertCol	Insert a column into the current matrix, increasing the column count of the matrix by one.
InsertRow	Insert a row into the current matrix, increasing the row count of the matrix by one.
Inv	Returns the inverse of the array. Gauss-Jordan is used.
IsNonZero	Returns true if a matrix element is non-zero.
LES_Solve	Solve a system of linear equations in the standard form Ax = b, where A is the coefficient matrix, b is the right hand side and x is the solution. If A is a square matrix, then LU Decomposition is used to solve for x. If A.NumRows > A.NumColumns, i.e. the system of equations is over determined, the QR algorithm is used to solve for x.
Load	Overloaded. These methods will open a text file and read the CSV (Comma Separated Value) formatted data values in that

	file. A CSV file can be created by popular spreadsheet and word processing programs. This version of Load assumes CSV values are organized in a ROW_MAJOR format.
LoadMM	Load a file that is in the Matrix Market format.
LU_Solve	Solve a system of linear equations (using LU Decomposition) in the standard form Ax = b, where A is the coefficient matrix, b is the right hand side and x is the solution.
MakeHilbert	Make a Hilbert matrix of the specified rank.
MatNull	Initializes the matrix to empty, 0 rows and 0 columns.
Norm	Calculate the a norm for the current matrix.
Norm1	Calculate the 1-norm of the current matrix.
Norm2	Calculate the 2-norm of the current matrix.
NormInf	Calculate the infinity-norm of the current matrix.
NumElRC	Returns the number of row or column elements in the matrix.
QR_Solve	Solve a system of linear equations (using QR Factorization) in the standard form Ax = b, where A is the coefficient matrix, b is the right hand side and x is the solution.
R	Overloaded. Returns the specified row as a vector.
RCInitialize	Initialize a row or a column to the specified value.
RCNorm	Returns the vector norm for a row or a column in the matrix.
RCSSQ	Returns the sum of squares for a row or a column in the current matrix.
RCSubInitialize	Initialize a sub-range of a row or a column to the specified value.
Reset	Initializes the matrix to empty, 0 rows and 0 columns.
Resize	Overloaded. Resize the vector. This is a non-destructive resize. Original data, to the extent that it fits into the new vector, is preserved.
Save	Overloaded. These methods will create a text file and output the dataset to that file in a CSV (Comma Separated Value) format. A CSV file can be read by popular spreadsheet and word

	processing programs. This version of Save assumes CSV values are organized in a ROW_MAJOR format.
SaveMM	Overloaded. Save the matrix to a file using the Matrix Market file format.
ScaleCol	Scale a column in the current matrix.
ScaleMat	Scale all of the elements of the current matrix
ScaleRow	Scale a row in the current matrix.
SetBaseOneMatrix	Set the current matrix as using a base one matrix.
SetCol	Overloaded. Set a column in the current matrix.
SetElement	Set an element of the matrix.
SetError	Set the current matrix error.
SetMatrix	Overloaded. Initializes the vector using the specified 1D array. Source array.
SetMatrix	Overloaded. High speed routine for copying a matrix. Uses System.Array.Copy.
SetRC	Overloaded. Set a row or a column.
SetRow	Overloaded. Set a row in the current matrix.
SetSize	Overloaded. Set the size of the matrix.
SetSubCol	Overloaded. Set a sub-range of a column in the current matrix.
SetSubRC	Overloaded. Set the sub-range of a row or a column.
SetSubRow	Overloaded. Set a sub-range of a row in the current matrix.
SetVector	Set the values of a matrix vector using a double array.
SetVectorElement	Set an element of the vector.
SSQ	Returns the sum of squares of all elements in the matrix.
Sum	Returns the sum of all elements in the matrix.

SumAbs	Returns the sum of the ABS of all elements in the matrix.
SwapCols	Swap a pair of columns of the current matrix.
SwapRows	Swap a pair of rows of the current matrix.
T	Returns the transpose of the current matrix.
ToString	Returns a String that represents the current Object.
Transp	Transpose the current matrix.

Chapter 5 - Solution of Linear Systems of Equations

LESBase
- **LESLU**
- **LESGJ**
- **LESCholesky**
- **LESQR**

LESXBase
- **LESXLU**
- **LESXGJ**
- **LESXCholesky**
- **LESXQR**

The central problem of linear algebra and one of the most common numerical problems encountered is the solution of a set of linear equations. Typically, this takes the form of equations that when fully written out look something like the equations below.

$$\begin{aligned} 3x_1 &+ 2x_2 - x_3 = 1 \\ 2x_1 &- 2x_2 + 4x_3 = -2 \\ -x_1 &+ \tfrac{1}{2}x_2 - x_3 = 0 \end{aligned}$$

The coefficients of the left hand side are the numbers in front of the x1, x2 and x3 variables and are usually referred to as the coefficient matrix variable A. The numbers of the right hand side, 1, -2, 0 in this case, are usually referred to as the *rhs*, or the matrix variable b. The x's, or unknowns, are referred to using the matrix variable x. When written in matrix format, the system of equations above is written as:

Ax = b

where,

A = $\begin{bmatrix} 3 & 2 & -1 \\ 2 & -2 & 4 \\ -1 & 0.5 & -1 \end{bmatrix}$ and **b** = $\begin{bmatrix} 1 \\ -2 \\ 0 \end{bmatrix}$

The solution, x, to this particular set of equations is:

x = $\begin{bmatrix} 1 \\ -2 \\ -2 \end{bmatrix}$

The matrix representation is generalized for systems of equations of any size, whether 2 x 2 or 10000 x 10000. The real number example above can be further generalized to the domain of complex numbers.

Solving large systems of equations is a critical element in almost every engineering discipline. Typical applications include circuit analysis, finite element analysis, digital signal processing, forecasting, simulation, econometrics, linear programming, robotics, computer animation, genetic engineering, nuclear engineering, etc. The list is endless.

The first formal method for solving systems of simultaneous equations is usually attributed to Frederick Gauss, the 19th century German mathematician. His general algorithm was further improved over the years and appears here in the numerically most stable form, Gauss-Jordan with partial pivoting. Other algorithms included in the software include LU Decomposition, QR Factorization (or Decomposition), and Cholesky Decomposition. Each algorithm has specific benefits, and weaknesses, you need to consider when deciding which algorithm to use. Each algorithm is supplied in versions for both real and complex numbers.

Algorithm	**Strengths**	**Weaknesses**
Gauss-Jordan	Stable for all but the most ill-conditioned of matrices. Produces the inverse of the coefficient matrix (A) as a by-product. Produces a solution in finite time on the order of $2n^3 / 3$ operations.	The slowest of the four algorithms presented here. Since it does not produce an intermediate matrix factorization, it is not the recommended algorithm if you need to be able to solve multiple right hand sides (b) for the same coefficient matrix (A). Requires a square coefficient matrix (A).
LU	Stable for all but the most ill-conditioned of matrices. Faster than Gauss-Jordan when used to solve for one right hand side. Produces an intermediate matrix factorization that can be used for high-speed solution of multiple right hand sides using back-substitution. Produces a solution in finite time on the order of $2n^3 / 3$ operations.	Not as fast as Cholesky decomposition in solving symmetric, positive, definite matrices. Requires a square coefficient matrix (A).
QR	Stable for all but the most ill-conditioned of matrices. Faster than Gauss-Jordan when used to	Not as fast as Cholesky decomposition in solving symmetric,

	solve for one right hand side. Produces an intermediate matrix factorization that can be used for high-speed solution of multiple right hand sides using back-substitution. Can be used for solving over-determined systems of equations, where the number of rows is greater than the number of columns. Produces a solution in finite time on the order of $2n^3 / 3$ operations.	positive, definite matrices.
Cholesky	The fastest of the four algorithms. Produces an intermediate matrix factorization that can be used for high-speed solution of multiple right hand sides using back-substitution. Produces a solution in finite time on the order of $n^3 / 3$ operations, or about twice as fast as LU decomposition.	Requires that the coefficient matrix is a symmetric, positive, definite matrix.

Standard Interface for the Solution of Linear Equations

The linear equations solving classes all use the same interface. You define the problem by passing the coefficient matrix A in the constructor of the class you are using. In the case of LU, QR and Cholesky, the coefficient matrix is immediately factored into intermediate matrices. The programmer then calls the **Solve** method, passing in a matrix of one or more right hand sides (b). The solution is calculated using the intermediate matrices and back substitution and returned in the same **Solve** method call. The Gauss-Jordan algorithm does not factor the coefficient matrix into intermediate matrices, and the 100% of the algorithm takes place when the **Solve** method is called. The **Inverse** method returns the coefficient matrix inverse. The **CheckSolution** method will check the accuracy of a solution by calculating right hand side values based on the original coefficient matrix and solution, and comparing the results to the actual right hand side values.

The problem presented in the first page of the chapter is solved below using each of the four algorithms.

[C#]

```
double [,] aData = {{3,2,-1},{2,-2,4},{-1, 0.5, -1}};
double [] bData = {1, -2, 0};

DDMat A = new DDMat(aData);
DDMat b = new DDMat(bData);

DDMat x = new DDMat();
A.LES_Solve(b,x);


// LU Decomposition
LESLU leslu = new LESLU(A);
leslu.Solve(b,x);

// Gauss-Jordan
LESGJ lesgj = new LESGJ (A);
lesgj.Solve(b,x);

// QR Factorization
LESQR lesqr = new LESQR (A);
lesqr.Solve(b,x);
```

```
[VB]
Dim aData As Double(,) = {{3, 2, -1}, {2, -2, 4}, {-1, 0.5, -1}}
Dim bData As Double() = {1, -2, 0}

Dim A As New DDMat(aData)
Dim b As New DDMat(bData)

Dim x As New DDMat()
A.LES_Solve(b, x)

' LU Decomposition
 Dim leslu As New LESLU(A)
 leslu.Solve(b, x)

' Gauss-Jordan
Dim lesgj As New LESGJ(A)
lesgj.Solve(b, x)

 ' QR Factorization
Dim lesqr As New LESQR(A)
lesqr.Solve(b, x)
```

While the Cholesky algorithm is used in exactly the same way, it will fail for the example above because the coefficient matrix (A) is not symmetric-positive-definite. A symmetric, positive definite matrix is used in the example below.

```
[C#]
// Cholesky Decomposition
// Cholesky requires a symmetric-positive-definite matrix
double [,] aSPDData = {{ 13,   2,   -1},
                       {  2,   22,    4},
                       { -1,    4,   15}};
DDMat ASPD = new DDMat(aSPDData);
LESCholesky leschol = new LESCholesky (ASPD);
leschol.Solve(b,x);

[VB]
' Cholesky Decomposition
' Cholesky requires a symmetric-positive-definite matrix
Dim aSPDData As Double(,) = {{13, 2, -1}, {2, 22, 4}, {-1, 4, 15}}
Dim ASPD As New DDMat(aSPDData)
Dim leschol As New LESCholesky(ASPD)
leschol.Solve(b, x)
```

The complex versions of the same algorithms follow exactly the same logic, except that **DComplex** objects are used instead of doubles, and complex **DXMat** matrices are used instead of real **DDMat** matrices.

```
[C#]
double [,] arData = {{1.6,2.9,8.7}, {5.6,6.1,7.4}, {4.5, 4.8, 3.2}};
double [,] aiData = {{8.7,2.2,6.1}, {7.4,2.5,3.4}, {5.4, 8.1, 3.0}};

double [] brData = {0.0, 20, -10};
double [] biData = {60, 60, 50};

DXMat A = new DXMat(arData, aiData);
DXMat b = new DXMat(brData, biData);
DXMat x = new DXMat();
DXMat invA = new DXMat ();
DXMat residuals = new DXMat ();
double maxerr = 1.0e-8;
bool ok = true;
```

```
// LU Decomposition
LESXLU leslu = new LESXLU(A);
leslu.Solve(b,x);
leslu.Inverse(invA);
ok = leslu.CheckSolution(x, b, residuals, ref maxerr);

[VB]
double [,] arData = {{1.6,2.9,8.7}, {5.6,6.1,7.4}, {4.5, 4.8, 3.2}};
double [,] aiData = {{8.7,2.2,6.1}, {7.4,2.5,3.4}, {5.4, 8.1, 3.0}};

double [] brData = {0.0, 20, -10};
double [] biData = {60, 60, 50};

DXMat A = new DXMat(arData, aiData);
DXMat b = new DXMat(brData, biData);
DXMat x = new DXMat();

A.LES_Solve(b,x);

// LU Decomposition
LESXLU leslu = new LESXLU(A);
leslu.Solve(b,x);
```

Gauss-Jordan

Class LESGJ, LESXGJ

The **LESGJ**, and **LESXGJ** classes implement the Gauss-Jordan with partial pivoting algorithm, the most stable version of the Gauss-Jordan algorithm. Gaussian elimination turns the original, square, non-singular, system of equations into one that is upper triangular using a technique of subtracting multiples of one equation from another. Once the system of equations is upper triangular, the solution is solved for using simple back substitution. The partial pivoting enhancement of the algorithm ensures that extremely small values are not selected as equation multipliers, which can introduce round-off errors that lower the numerical accuracy of the solution. The algorithm produces the inverse of the original coefficient matrix as a by-product.

LESGJ, LESXGJ Constructors

LESGJ

```
[VB]    Public Sub New(  ByVal a As DMatBase )
```

```
[C#]    public LESGJ(   DMatBase a);
```

LESXGJ

```
[VB]    Public Sub New(  ByVal a As XMatBase )
[C#]    public LESGJ(   XMatBase a);
```

Parameters

a The coefficient matrix, A, for the Ax = b system of equations.

Example

The code in the **Standard Interface for the Solution of Linear Equations** section is extracted from the SimpleLES and SimpleLESX example programs. The class is also used in the LESTest and LESXTest example programs.

LU Decomposition

Class LESLU, LESXLU

The **LESLU**, and **LESXLU** classes implement the Crout version of the LU decomposition algorithm. LU decomposition starts with the standard definition of a linear system of equations, Ax = b, where A is square (n equations for n unknowns). It factors the non-singular matrix A into the matrix product, A = LU, of a lower triangular matrix L and upper triangular matrix U with unit diagonal. The resulting linear algebra equation LUx = b is solved for x. Most of the work is done in the factoring or A into the L and U matrices. Once L and U are calculated, for a given right hand side, b, the solution x, can be quickly calculated using a combination of forward and back substitution. For a single right hand side, the LU decomposition algorithm is two to three times faster than Gauss-Jordan algorithm. Since the LU matrices do not need to be recalculated for each new right hand side, it is even faster if you are solving for multiple right hand sides.

Unlike the Gauss-Jordan algorithm, the LU algorithm does not produce a matrix inverse as a by-product. If you call the **Inverse** method, the inverse is calculated by solving the Ax = b equation using b (b is a square matrix in this case with the same dimensions as A) as the identity matrix. If Ax = b, and b is the identity matrix, then x must be the inverse of A. Solving for x produces the inverse of A.

LESLU, LESXLU Constructors

LESLU

```
[VB]    Public Sub New(  ByVal a As DMatBase )
[C#]    public LESLU(   DMatBase a);
```

LESXLU

```
[VB]    Public Sub New(  ByVal a As XMatBase )
[C#]    public LESLU(   XMatBase a);
```

Parameters

a The coefficient matrix, A, for the Ax = b system of equations.

Example

The code in the **Standard Interface for the Solution of Linear Equations** section is extracted from the SimpleLES and SimpleLESX example programs. The class is also used in the LESTest and LESXTest example programs.

QR Factorization

Class LESQR, LESXQR

The **LESQR**, and **LESXQR** classes implement the QR factorization by way of a Householder reflections algorithm. QR factorization starts with the standard definition of a linear system of equations, Ax = b. Unlike Gauss-Jordan, LU or Cholesky algorithms, the A matrix does not have to be square. The system of equations can be over-determined, where the number of equations is greater than the number of unknowns, producing an m x n matrix (number of equations x number of unknowns) with m >= n. The algorithm factors the non-singular matrix A into the matrix product A = QR of an orthogonal matrix Q and upper triangular matrix R. The resulting linear algebra equation, QRx = b, is solved for x. Most of the work is done in the factoring or A into the Q and R matrices. Once Q and R are calculated, for a given right hand side, b, the solution x, can be quickly calculated using a combination of forward and back substitution. For a single right hand side, the QR decomposition algorithm is two to three times faster than Gauss-Jordan algorithm. Since the QR matrices do not need to be recalculated for each new right hand side, it is even faster if you are solving for multiple right hand sides.

Unlike the Gauss-Jordan algorithm, the QR algorithm does not produce a matrix inverse as a by-product. If you call the **Inverse** method, the inverse is calculated by solving the Ax = b equation using b (b is a square matrix in this case with the A dimensions (n x n) as the identity matrix. If Ax = b, and b is the identity matrix, then x must be the inverse of A. Solving for x produces the inverse of A.

When the QR algorithm is solving for the over determined case where the number of equations exceeds the number of unknowns, the result is the same as a multiple regression problem run on the same data. The solution are the values that minimize the

sum of the residual errors squared, usually referred to as the linear least squares solution to the problem.

LESQR, LESXQR Constructors

LESQR

```
[VB]    Public Sub New(  ByVal a As DMatBase )
[C#]    public LESQR(   DMatBase a);
```

LESXQR

```
[VB]    Public Sub New(  ByVal a As XMatBase )
[C#]    public LESQR(   XMatBase a);
```

Parameters

a The coefficient matrix, A, for the Ax = b system of equations.

Example

The code in the **Standard Interface for the Solution of Linear Equations** section is extracted from the SimpleLES and SimpleLESX example programs. The class is also used in the LESTest and LESXTest example programs.

Cholesky Decomposition

Class LESCholesky, LESXCholesky

The **LESCholesky**, and **LESXCholesky** classes implement the Cholesky decomposition algorithm. Cholesky decomposition starts with the standard definition of a linear system of equations, Ax = b. The coefficient matrix A must be symmetric-positive-definite in order for the algorithm to work. The Cholesky algorithm factors the non-singular matrix A into the matrix product of an upper and lower triangular matrix A = LU (much like the LU algorithm). In this case, L and U are specially factored so that it U is the transpose of L. So the equation becomes $A = LL^*$. The resulting linear algebra equation $LL^*x = b$ is solved for x. Most of the work is done in the factoring of the L matrix. Once L is calculated, for a given right hand side, b, the solution x, can be quickly calculated using a combination of forward and back substitution. For a single right hand side, the Cholesky decomposition algorithm is two to three times faster than the LU algorithm. Since the Cholesky L matrix does not need to be recalculated for each new right hand side, it is even faster if you are solving for multiple right hand sides.

Unlike the Gauss-Jordan algorithm, the Cholesky algorithm does not produce a matrix inverse as a by-product. If you call the **Inverse** method, the inverse is calculated by solving the Ax = b equation using b (b is a square matrix in this case with the same dimensions as A) as the identity matrix. If Ax = b, and b is the identity matrix, then x must be the inverse of A. Solving for x produces the inverse of A.

In the complex version of the algorithm (**LESXCholesky**), the coefficient matrix, A, must be Hermitian-positive-definite, since Hermitian is the complex equivalent of the real symmetric. Since L is complex, L^* is the conjugate transpose of L.

LESCholesky, LESXCholesky Constructors

LESCholesky

```
[VB]    Public Sub New(  ByVal a As DMatBase )
[C#]    public LESCholesky (   DMatBase a);
```

LESXCholesky

```
[VB]    Public Sub New(  ByVal a As XMatBase )
[C#]    public LESCholesky (   XMatBase a);
```

Parameters

a The coefficient matrix, A, for the Ax = b system of equations.

Example

The code in the **Standard Interface for the Solution of Linear Equations** section is extracted from the SimpleLES and SimpleLESX example programs. The class is also used in the LESTest and LESXTest example programs.

Selected LESGJ, LESXGJ Methods

LESGJ.Solve, LESXGJ.Solve Methods

Solve the square, non-singular, system of equations represented by the matrix equation Ax = b using the Gauss-Jordan with partial pivoting algorithm. If the right hand side matrix, b, has more than one column, a solution for each column is returned in the columns of the solution matrix x.

LESGJ

```
[VB]    Public Function GJ_Solve(  ByVal b As DMatBase,
        ByVal x As DMatBase ) As Integer
```

```
[C#]    public int GJ_Solve( DMatBase b,  DMatBase x);
```

LESXGJ

```
[VB]    Public Function GJ_Solve(  ByVal b As XMatBase,
        ByVal x As XMatBase ) As Integer
[C#]    public int GJ_Solve( XMatBase b,  XMatBase x);
```

Parameters

b The right hand side matrix, b, for the system of equations Ax = b. The right hand side values of b are stored as a column vector. If b has more then one column, representing multiple right hand sides, the solution, x, will have more than one column, one column for each solution.

x Returns the solution(s), x, to the system Ax = b. If b has more then one column, representing multiple right hand sides, the solution, x, will have more than one column, one column for each solution.

Example

The code in the **Standard Interface for the Solution of Linear Equations** section is extracted from the SimpleLES and SimpleLESX example programs. The class is also used in the LESTest and LESXTest example programs.

Chapter 6 – Eigenvalue and Eigenvector Solutions

EigenBase
- **EigenQR**
- **EigenQL**
- **EigenQR2**

EigenXBase
- **EigenXLR**

Eigenvalues and eigenvectors provide very important tools for analysis of many physical systems. The eigenvalue problem is to find the non-trivial solutions of the equation:

$$\mathbf{AX = \lambda X}$$

where A is a n x n matrix, X is a vector of length n, and λ is a scalar. This equation involves two unknowns λ and X. The n values of λ that satisfy the equation are the eigenvalues of matrix A, and the corresponding values of X are its right eigenvectors. For example:

$$A \quad X \quad = \quad \lambda \quad X$$

$$\begin{bmatrix} 5 & 4 & 1 & 1 \\ 4 & 5 & 1 & 1 \\ 1 & 1 & 4 & 2 \\ 1 & 1 & 2 & 4 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -1 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -2 \\ 2 \end{bmatrix} = 2 \begin{bmatrix} 0 \\ 0 \\ -1 \\ 1 \end{bmatrix}$$

The eigenvalue λ in this case is 2 and the eigenvector associated with λ is

$$\begin{bmatrix} 0 \\ 0 \\ -1 \\ 1 \end{bmatrix}$$

To find the eigenvalues of a matrix A, rewrite the equation $AX = \lambda X$ as

$$\begin{aligned} AX &= \lambda IX \\ AX - \lambda IX &= 0 \\ (A - \lambda I)X &= 0 \end{aligned}$$

We want to find the numbers for λ for which the equation above has non-zero solutions X, which is the same as finding the numbers for that make $\det(A - \lambda I) = 0$. This is referred to as the characteristic equation of A. The left hand side of the equation is the characteristic polynomial of A. For the matrix:

$$A = \begin{bmatrix} 5 & 4 & 1 & 1 \\ 4 & 5 & 1 & 1 \\ 1 & 1 & 4 & 2 \\ 1 & 1 & 2 & 4 \end{bmatrix}$$

$$A - \lambda I = \begin{bmatrix} 5 & 4 & 1 & 1 \\ 4 & 5 & 1 & 1 \\ 1 & 1 & 4 & 2 \\ 1 & 1 & 2 & 4 \end{bmatrix} - \begin{bmatrix} \lambda & 0 & 0 & 0 \\ 0 & \lambda & 0 & 0 \\ 0 & 0 & \lambda & 0 \\ 0 & 0 & 0 & \lambda \end{bmatrix} = \begin{bmatrix} 5-\lambda & 4 & 1 & 1 \\ 4 & 5-\lambda & 1 & 1 \\ 1 & 1 & 4-\lambda & 2 \\ 1 & 1 & 2 & 4-\lambda \end{bmatrix}$$

The characteristic equation $\det(A - \lambda I) = 0$ can be written as follows:

$$\det\begin{bmatrix} 5-\lambda & 4 & 1 & 1 \\ 4 & 5-\lambda & 1 & 1 \\ 1 & 1 & 4-\lambda & 2 \\ 1 & 1 & 2 & 4-\lambda \end{bmatrix} = 0$$

Solving for the determinant will yield the following eigenvalues and their associated eigenvectors:

$$1\begin{bmatrix} -1 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \quad 2\begin{bmatrix} 0 \\ 0 \\ -1 \\ 1 \end{bmatrix}, \quad 5\begin{bmatrix} -0.5 \\ -0.5 \\ 1 \\ 1 \end{bmatrix}, \quad 10\begin{bmatrix} 1 \\ 1 \\ 0.5 \\ 0.5 \end{bmatrix}$$

Eigensystem problems are divided into different categories, depending on the symmetry of the original matrix, and whether or not the original matrix contains complex values. The class you should use depends on the category.

	Eigenvalues	**Eigenvectors**
	Class to Use	**Class to Use**
Source Matrix	**(solution numeric type)**	**(solution numeric type)**
Real-Symmetric	EigenQL	EigenQL
	(real)	(real)
Real-Unsymmetric	EigenQR	EigenQR2
	(complex)	(complex)
Complex Hermitian	EigenXLR	EigenXLR
	(complex)	(complex)
Complex Un-Hermitian	EigenXLR	EigenXLR
	(complex)	(complex)

If you have a real-symmetric matrix, use the **EigenQL** class for both eigenvalues and eigenvectors. If you have a real-unsymmetric matrix, use **EigenQR** for eigenvalues only and **EigenQR2** if you want eigenvalues and eigenvectors. If you have a complex matrix, of any type, use the **EigenXLR** class for both eigenvalues and eigenvectors.

Standard Interface for Eigenvalue and Eigenvectors Solutions

The eigen-problem classes use the same interface, with minor variants depending on whether or not the source matrix is real or complex, and whether or not the eigenvalues and eigenvectors are real or complex. You define the problem by passing the coefficient matrix A in the constructor of the class you are using. Real matrices of type **DDMat** use the **EigenQL**, **EigenQR** and **EigenQR2** classes. Complex matrices of type **DXMat** use the **EigenXLR** class. If you need only the eigenvalues of a matrix, use the **CalcEigenValues** method. If you need the eigenvalues and eigenvectors of a matrix, use the **CalcEigenValuesAndVectors**. The **CheckEigenVectors** method will check the accuracy of the solution by comparing the values $AX = \lambda X$.

QL Algorithm for Real Symmetric Matrices

Class EigenQL

The **EigenQL** class will calculate all of the eigenvalues and eigenvectors of a real-symmetric matrix using the implicit QL method.

EigenQL Constructor

```
[VB] Public Sub New(  ByVal a As DMatBase )
[C#] public EigenQL(  DMatBase a );
```

Parameters

a The source matrix for the eigensystem calculations. The source matrix MUST be real-symmetric.

Method CalcEigenValues

Calculate the real eigenvalues for the source matrix, A.

```
[VB] Public Function CalcEigenValues(ByVal eigval As DMatBase ) As Integer
[C#] public int CalcEigenValues( DMatBase eigval);
```

Parameters

eigval Returns the real eigenvalues of the source matrix A.

Return Value

Returns an error code.

Method CalcEigenValuesAndVectors

Calculate the real eigenvalues and eigenvectors for the source matrix, A.

```
[VB]  Public Function CalcEigenValuesAndVectors(
           ByVal eigval As DMatBase,
           ByVal eigvect As DMatBase

       ) As Integer


[C#] public int CalcEigenValuesAndVectors( DMatBase eigval, DMatBase eigvect);
```

Parameters

eigval Returns the real eigenvalues of the source matrix A.

eigvect Returns the real eigenvectors of the source matrix A.

Return Value

Returns an error code

Method CheckEigenVectors

The eigenvalues and eigenvectors of a matrix must satisfy the following equation: Ax = Lx, where A is the original matrix, L is an eigenvalue of A, and x is the eigenvector of A corresponding to eigenvalue L. Given the original matrix A, and the eigenvalues and eigenvectors of A, this method calculates Ax - Lx for each eigenvalue/eigenvector pair and compares the result to a threshold residual, returning true if the actual residual is less than the test threshold residual. This routine assumes the matrices use base-zero [0..N-1] indices.

```
[VB] Public Shared Function CheckEigenVectors(
   ByVal A As DMatBase,
   ByVal evalues As DMatBase,
   ByVal evectors As DMatBase,
   ByVal residuals As DMatBase,
   ByRef resid As Double ) As Boolean

[C#] public static bool CheckEigenVectors(
   DMatBase A,
   DMatBase evalues,
   DMatBase evectors,
   DMatBase residuals,
```

```
   ref double resid
);


[VB] Public Shared Function CheckEigenVectors(
   ByVal A As DMatBase,
   ByVal evalues As XMatBase,
   ByVal evectors As XMatBase,
   ByVal residuals As XMatBase,
   ByRef resid As Double ) As Boolean


[C#] public static bool CheckEigenVectors(
   DMatBase A,
   XMatBase evalues,
   XMatBase evectors,
   XMatBase residuals,
   ref double resid
);
```

Parameters

A The original real matrix.

evalues A vector of the eigenvalues for the matrix A.

evectors A matrix of the eigenvectors for the matrix A.

residuals Returns a vector containing the actual residuals of Ax - Lx.

resid A reference number, if all residuals of ABS(Ax - Lx) are less than resid, the method returns true. The maximum error is returned in *resid*.

Return Value

Returns true if the all of the residuals of Ax - Lx are less than the *resid* value.

Example

Code listing extracted from the EigenRealSym example program.

```
[C#]
DDMat A = new DDMat();
.
. // Matrix A needs to be initialized
.
// results returned in EValues and EVectors
DDMat EValues = new DDMat();
DDMat EVectors = new DDMat();
.
.
EigenQL eigensolve = new EigenQL(A);
```

```
eigensolve.CalcEigenValuesAndVectors(EValues, EVectors);


DDMat residuals = new DDMat(); // residuals returned here
double refnum = 1.0e-4; // if any residual > this value, solution
                        // invalid, returns actual max error
bool ok = EigenBase.CheckEigenVectors(A, EValues, EVectors, residuals, ref
refnum);


[VB]
Dim A As New DDMat()
.
.  ' Matrix A needs to be initialized
.
' results returned in EValues and EVectors
Dim EValues As New DDMat()
Dim EVectors As New DDMat()
.
.
Dim eigensolve As New EigenQL(A)
eigensolve.CalcEigenValuesAndVectors(EValues, EVectors)


Dim residuals As New DDMat() ' residuals returned here
Dim refnum As Double = 0.0001 ' if any residual > this value, solution
' invalid, returns actual max error
Dim ok As Boolean = EigenBase.CheckEigenVectors(A, EValues, EVectors, residuals,
refnum)
```

QR Algorithm for Real Unsymmetric Matrices

Class EigenQR

The **EigenQR** class will calculate all of the eigenvalues a real-symmetric matrix using the QR method. If you request the eigenvalues and eigenvectors from this class, it in turn calls the **EigenQR2** class, because that is the one that calculates eigenvectors for a real-unsymmetric matrix.

EigenQR Constructor

```
[VB] Public Sub New(  ByVal a As DMatBase )
[C#] public EigenQR(  DMatBase a );
```

Parameters

a The source matrix for the eigensystem calculations. The source matrix must be square, but it does not have to be symmetric.

Method CalcEigenValues

Calculate the real eigenvalues for the source matrix, A. Eigenvalues that have an imaginary part are discarded. Since a real unsymmetric matrix can produce real and complex eigenvalues, you probably want to be calling the **CalcEigenValues** method (next) that accepts a complex matrix instead.

```
[VB] Public Function CalcEigenValues(ByVal eigval As DMatBase ) As Integer
[C#] public int CalcEigenValues( DMatBase eigval);
```

Calculate the complex eigenvalues for the source matrix, A.

```
[VB] Public Function CalcEigenValues(ByVal eigval As XMatBase ) As Integer
[C#] public int CalcEigenValues( XMatBase eigval);
```

Parameters

eigval Returns the eigenvalues of the source matrix A.

Return Value

Returns an error code.

Method CalcEigenValuesAndVectors

Calculate the real eigenvalues and eigenvectors for the source matrix, A. Eigenvalues that have an imaginary part are discarded. Since a real unsymmetric matrix can produce real and complex eigenvalues, you probably want to be calling the **CalcEigenValues** method (next) that accepts a complex matrix instead.

```
[VB]  Public Function CalcEigenValuesAndVectors(
          ByVal eigval As DMatBase,
          ByVal eigvect As DMatBase
      ) As Integer

[C#] public int CalcEigenValuesAndVectors( DMatBase eigval, DMatBase eigvect);
```

Calculate the complex eigenvalues and eigenvectors for the source matrix, A.

```
[VB]  Public Function CalcEigenValuesAndVectors(
          ByVal eigval As XMatBase,
          ByVal eigvect As XMatBase
      ) As Integer
```

```
[C#] public int CalcEigenValuesAndVectors( XMatBase eigval, XMatBase eigvect);
```

Parameters

eigval Returns the eigenvalues of the source matrix A.

eigvect Returns the eigenvectors of the source matrix A.

Return Value

Returns an error code

Example

See code listing under EigenQR2.

Class EigenQR2

The **EigenQR** class will calculate all of the eigenvalues and eigenvectors for a real-symmetric matrix using the implicit QR method.

EigenQR2 Constructor

```
[VB] Public Sub New(  ByVal a As DMatBase )
[C#] public EigenQR2(  DMatBase a );
```

Parameters

a The source matrix for the eigensystem calculations. The source matrix must be square, but it does not have to be symmetric.

Method CalcEigenValues

Calculate the complex eigenvalues for the source matrix, A.

```
[VB] Public Function CalcEigenValues(ByVal eigval As XMatBase ) As Integer
[C#] public int CalcEigenValues( XMatBase eigval);
```

Parameters

eigval Returns the eigenvalues of the source matrix A.

Return Value

Returns an error code.

Method CalcEigenValuesAndVectors

Calculate the complex eigenvalues and eigenvectors for the source matrix, A.

```
[VB]  Public Function CalcEigenValuesAndVectors(
           ByVal eigval As XMatBase,
           ByVal eigvect As XMatBase

       ) As Integer


[C#] public int CalcEigenValuesAndVectors( XMatBase eigval, XMatBase eigvect);
```

Parameters

eigval Returns the eigenvalues of the source matrix A.

eigvect Returns the eigenvectors of the source matrix A.

Return Value

Returns an error code

Example

Code listing extracted from the EigenRealUnSym example program.

```
[C#]
DDMat A = new DDMat();
.
. // Matrix A needs to be initialized
.
// results returned in EValues and EVectors
DXMat EValues = new DXMat();
DXMat EVectors = new DXMat();.
.
.
EigenQR2 eigensolve = new EigenQR2(A);
eigensolve.CalcEigenValuesAndVectors(EValues, EVectors);


DXMat residuals = new DXMat(); // residuals returned here
double refnum = 1.0e-4; // if any residual > this value,
                        // solution invalid, returns actual max error
bool ok = EigenXBase.CheckEigenVectors(A, EValues, EVectors, residuals, ref
refnum);
```

```
[VB]
Dim A As New DDMat()
.
.
.
Dim EValues As New DXMat()
Dim EVectors As New DXMat()
.
.
eigensolve = New EigenQR2(A) '
eigensolve.CalcEigenValuesAndVectors(EValues, EVectors)


Dim residuals As New DXMat() ' residuals returned here
Dim refnum As Double = 0.0001 ' if any residual > this value,
' solution invalid, returns actual max error
Dim ok As Boolean = EigenXBase.CheckEigenVectors(A, EValues, EVectors, residuals,
refnum)
```

LR Algorithm for Complex Matrices

Class EigenXLR

The **EigenXLR** class will calculate all of the eigenvalues and eigenvectors for a complex matrix using the LR method. There are no symmetry constraints.

EigenXLR Constructor

```
[VB] Public Sub New(  ByVal a As XMatBase )
[C#] public EigenXLR(  XMatBase a );
```

Parameters

a The source matrix for the eigensystem calculations. The source matrix must be square, but it does not have to be symmetric.

Method CalcEigenValues

Calculate the complex eigenvalues for the source matrix, A.

```
[VB] Public Function CalcEigenValues(ByVal eigval As XMatBase ) As Integer
[C#] public int CalcEigenValues( XMatBase eigval);
```

Parameters

eigval Returns the eigenvalues of the source matrix A.

Return Value

Returns an error code.

Method CalcEigenValuesAndVectors

Calculate the complex eigenvalues and eigenvectors for the source matrix, A.

```
[VB]  Public Function CalcEigenValuesAndVectors(
           ByVal eigval As XMatBase,
           ByVal eigvect As XMatBase

       ) As Integer


[C#] public int CalcEigenValuesAndVectors( XMatBase eigval, XMatBase eigvect);
```

Parameters

eigval Returns the eigenvalues of the source matrix A.

eigvect Returns the eigenvectors of the source matrix A.

Return Value

Returns an error code

Method EigenXBase.CheckEigenVectors

The eigenvalues and eigenvectors of a matrix must satisfy the following equation: Ax = Lx, where A is the original matrix, L is an eigenvalue of A, and x is the eigenvector of A corresponding to eigenvalue L. Given the original matrix A, and the eigenvalues and eigenvectors of A, this method calculates Ax - Lx for each eigenvalue/eigenvector pair and compares the result to a threshold residual, returning true if the actual residual is less than the test threshold residual. This routine assumes the matrices use base-zero [0..N-1] indices.

```
[VB]  Public Shared Function CheckEigenVectors(
   ByVal A As XMatBase,
   ByVal evalues As XMatBase,
   ByVal evectors As XMatBase,
   ByVal residuals As XMatBase,
   ByRef resid As Double ) As Boolean
```

```
[C#] public static bool CheckEigenVectors(
   XMatBase A,
   XMatBase evalues,
   XMatBase evectors,
   XMatBase residuals,
   ref double resid
);
```

Parameters

A The original, complex, matrix.

evalues A vector of the eigenvalues for the matrix A.

evectors A matrix of the eigenvectors for the matrix A.

residuals Returns a vector containing the actual residuals of Ax - Lx.

resid A reference number, if all residuals of ABS(Ax - Lx) is less than *resid*, the method returns true.

Return Value

Returns true if the all of the residuals of Ax - Lx are less than the *resid* value.

Example

Code listing extracted from the EigenComplex example program

```
[C#]
DXMat A= new DXMat();
.
. // Initialize complex matrix
.
DXMat EValues1 = new DXMat();
DXMat EVectors1 = new DXMat();

EigenXLR eigensolve1 = new EigenXLR(A);
eigensolve1.CalcEigenValuesAndVectors(EValues1, EVectors1);

DXMat residuals = new DXMat();
double resid = 1.0e-5;
bool ok1 = EigenXLR.CheckEigenVectors(A, EValues1,
                EVectors1, residuals, ref  resid);

DXMat residuals = new DXMat(); // residuals returned here
double refnum = 1.0e-4; // if any residual > this value, solution invalid, returns
                        // actual max error
```

```
bool ok = EigenXBase.CheckEigenVectors(A, EValues, EVectors, residuals, ref
refnum);


[VB]
Dim A As New DXMat()
.
.
.
Dim EValues1 As New DXMat()
Dim EVectors1 As New DXMat()
.
.
Dim eigensolve1 As New EigenXLR(A)
eigensolve1.CalcEigenValuesAndVectors(EValues1, EVectors1)


Dim residuals As New DXMat()
Dim resid As Double = 1E-05
Dim ok1 As Boolean = EigenXLR.CheckEigenVectors(A, EValues1, EVectors1, residuals,
resid)


Dim residuals As New DXMat() ' residuals returned here
Dim refnum As Double = 0.0001 ' if any residual > this value, solution invalid,
returns
' actual max error
Dim ok As Boolean = EigenXBase.CheckEigenVectors(A, EValues, EVectors, residuals,
refnum)
```

Chapter 7 – Multiple Regression

Regression analysis is a statistical tool for the evaluation of the relationship of one or more independent variables $X_1, X_2, \ldots X_k$ to a single dependent variable Y for a fixed number of observations. The primary goal of regression analysis is to obtain predictions of Y using the known values of X. These predictions are made using a regression equation. They are subject to error and are only estimates of the true values of Y. There can be other goals of regression analysis, for example, to determine which of several independent variables are important and which are not for describing and predicting a dependent variable. The simplest case of regression is known as simple linear regression and it calculates the relationship between one variable x and another one y. The relationship is considered linear because it is assumed that the underlying equation relating the two variables is of the form: y = mx + b.

Simple linear regression would take a list of (x,y) pairs (2 would be the minimum number of pairs) and calculate the slope coefficient, m, and the offset coefficient, *b*. Regression does not always return the exact values for the slope and offset because the data is usually empirical. The calculated slope and offset represent the best trend line which can be fitted through the data. The estimate is calculated using an algorithm which minimizes the sum of the squares of the vertical deviations separating the trend line from the actual data points. This algorithm is known as the method of least squares and it is by far the most common technique used in regression analysis.

Simple linear regression only handles equations for two variables. Multiple linear regression deals with equations of at least two variables. It is quite possible to provide estimates of equations of 100 or more variables using multiple regression. Large economic forecasting models use multiple regression to analyze data involving hundreds of variables.

The general form of a regression equation or model for *k* independent variables is given by the equation:

$$Y = b_0 + b_1 X_1 + b_2 X_2 + \ldots + b_k X_k$$

where $b_0, b_1, b_2, \ldots b_k$ are the regression coefficients that need to be estimated. The variable Y is the dependent variable in the equation above. The variables, $X_1, X_2, \ldots X_k$, are the independent variables. The objective of regression is to calculate the coefficients $b_0, b_1, b_2, \ldots b_k$ in order to produce the best estimates of the dependent variable Y given the values of the independent variables $X_1, X_2, \ldots X_k$.

The independent and dependent variables are all measured values. To calculate the coefficients you must first acquire enough data so that you have at least one more set of observations than the number of variables you are trying to fit. One of the most important measures of the quality of the regression equation fit is known as the correlation coefficient. The correlation coefficient is usually abbreviated as the r-value (R) of the

regression. The closer this value is to 1, the better the fit. Another measure of the fit is called the coefficient of determination, usually referred to as the r^2 (R^2) value. This value is equal to the square of the correlation coefficient. Again, the closer this value is to 1, the better the fit. The standard error of the estimate (usually abbreviated SEE), is yet another measure of the quality of the regression fit. It is a measure of the scatter of the actual data about the regression line. The smaller the SEE value, the closer the actual data is to the theoretical regression line. If you would like to learn more about the uses of regression, any good college textbook on statistics should cover the basics. Many graduate school textbooks are devoted entirely to the uses and interpretation of the results of regression. The mathematics behind the actual calculations involved in least squares multiple regression can be found in textbooks devoted to linear algebra and matrix math.

We provide several algorithms multiple regression – the standard least squares approach, which regresses only the independent variables you specify, and three other methods, forward selection, backward elimination and stepwise selection, which automatically choose the final regression coefficients, starting with your best guess, and eliminating variables with marginal F-Test statistics. They have different properties and each one can be the best for a particular regression problem and specific data set. As a rule, in case of not very highly correlated independent variables, the model obtained using general standard least squares regression will produce the smallest error if checked on the same data set on which it was built. The other methods produce results slightly less accurate, but simpler and more reliable, models.

Least Squares Multiple Regression

Class MulReg

MulReg

The **MulReg** class uses the least squares method of fitting data to an equation. It chooses regression equation coefficients that minimize the sum of the squares of the distances between the observed responses and those predicted by the fitted model. This sum of squares is called the residual sum of squares, or SEE. The class includes in the final regression equation all of the independent variables, except for those explicitly excluded by the consideration property or method.

In matrix math form, the algorithm is as follows:

X = matrix of independent variable values,

Y = vector of dependent variable values,

B = vector of regression coefficients to solve for.

The objective of the regression is to solve for B given X and Y. First, the data matrix X is converted into the square matrix A by multiplying it by its own transpose.

$$A = X^T X$$

A constant vector C is calculated by multiplying the transposed data matrix X by the dependent variable Y.

$$C = X^T Y$$

The solution vector B is calculated by solving the linear system of equations (remember Ax = b)

$$AB = C,$$

for the unknown B, using one of the equation solving algorithms: Gauss-Jordan, LU decomposition, Cholesky decomposition, or QR factorization. The Cholesky decomposition algorithm can be used because the A matrix ($X^T X$) will always be symmetric, positive, definite. B is a vector that returns the coefficients of the least squares multiple regression fit to the original data.

This method works well if the independent variables are not highly correlated with each other, and if most of them contribute significantly to the dependent variable. Otherwise, it may encounter problems. For example, if two of the independent variables are highly, or perfectly, correlated, the linear equations may become ill-conditioned and produce erroneous results. If there are many independent variables which are not correlated with the dependent one, they will never less all be included in the model and the model may be unreliable as a result.

MulReg constructor

Set up a multiple regression, including all of the independent variables in the final solution.

```
[Visual Basic]
Overloads Public Sub New(
   ByVal iv As DMatBase,
   ByVal dv As DMatBase
)
[C#]
public MulReg(
   DMatBase iv,
   DMatBase dv
);
```

Set up a multiple regression, including only the independent variables flagged by the *consid* vector in the final solution.

```
[Visual Basic]
Overloads Public Sub New(
   ByVal iv As DMatBase,
   ByVal dv As DMatBase,
   ByVal consid As IVect _
)
[C#]
public MulReg(
   DMatBase iv,
   DMatBase dv,
   IVect consid
);
```

iv A matrix of the independent variable (x-values).
dv A matrix of the dependent variable (y-values).
consid A vector contains consideration values, one for each independent variable i the *iv* array, plus the constant. Element 0 contains the constant flag, the other elements contain the flags for the iv array. Initialize the array elements using one of the consider constants: REG_VARIN, REG_VAROUT, REG_VARCONSIDER. If an element is REG_VARIN, or REG_VARCONSIDER, the corresponding variable is included in the regression.

Use the **Solve** method to solve the current multiple regression using the current parameters. The methods returns the regression equation coefficients, and summary regression statistics.

Method MulReg.Solve

```
 [Visual Basic]
Overloads Public Function Solve( _
   ByVal regcoef As DDMat, _
   ByVal regstats As RegStats _
) As Integer
[C#]
public int Solve(
   DDMat regcoef,
   RegStats regstats
);
```

Parameters

regcoef Returns the calculated regression coefficients.
regstats Returns regression statistics. The **RegStats** class is a simple class that encapsulates several related summary statistics for multiple regression:

RegStats class

Public Instance Properties

Ovfst — Get/Set overall F statistic

R	Get/Set multiple correlation coefficient (R-value)
Rsq	Get/Set coefficient of determination (R-Squared)
See	Get/Set Returns the Standard error of estimate (
Sigflag	Get/Set significance of regression flag
Sumressq	Get/Set sum of residuals squared

Multiple regression example – Extracted from the example program Mulregtest.

```
[C#]
MulReg mulreg = new MulReg();
DDMat A = new DDMat(); // Independent variable matrix
DDMat RHS = new DDMat(); // Ddependent variable matrix
.
.
// Initialize A and RHS matrices;

mulreg = new MulReg (A, RHS);
for (int i=0; i < mulreg.IndependentVariables.NumColumns + 1; i++)
    mulreg.SetConsider(i,MulReg.REG_VARIN);

RegStats regstats = new RegStats();
DDMat coefficients = new DDMat();
mulreg.Solve(coefficients, regstats);


[Visual Basic]
Dim mulreg As New MulReg()
Dim A As New DDMat() ' Independent variable matrix
Dim RHS As New DDMat() ' Ddependent variable matrix
.
.
.
mulreg = New MulReg(A, RHS)
Dim i As Integer
For i = 0 To (mulreg.IndependentVariables.NumColumns + 1) - 1
   mulreg.SetConsider(i, MulReg.REG_VARIN)
```

```
Next i

Dim regstats As New RegStats()

Dim coefficients As New DDMat()

mulreg.Solve(coefficients, regstats)
```

Other useful regression statistics can be calculated on demand. These include the partial F- statistics. F-Test statistics can take a lot of time to calculated, since it involves as many separate multiple regressions as there are independent variables. Call the method **FTestAnalysis** to calculate the F-statistics.

Method MulReg.FTestAnalysis

```
 [Visual Basic]
Overloads Public Function FTestAnalysis( _
   ByVal fstat As DDMat, _
   ByVal conf_level As Double _
   ByVal coefsig As DDMat, _
) As Integer

[C#]
public int FTestAnalysis(
   DDMat fstat,
   double conf_level,
   DDMat coefsig
);
```

Parameters

fstat Returns the calculated f-statistics, one for each independent variable.

conf_level A fractional value (usually between 0.8 to 0.99) specifying the confidence level. An independent variable is considered significant if the probability of it being significant exceeds this confidence level.

coefsig Returns an array of flags, one for each independent variable. If the value of an array element is 1, that means that the probably of the corresponding independent variable being significant exceeds the specified confidence level.

Automatic Selection of Regression Variables

Class StepwiseMulReg

The **MulReg** class allows the programmer to include and exclude independent variables from the final regression equation using the consider (*consid*) parameter of the **MulReg** constructor. Another approach is to let the program decide what independent variables to include in the final regression equation. The **StepwiseMulReg** class includes three algorithms for the automatic selection of the independent variables used in the regression model: backward elimination, forward selection, and stepwise selection. You can still force variables in and out using the *consider* parameter of the constructor. The selection mechanism will choose between variables marked REG_VARCONSIDER. Those

marked with REG_VARIN will be included in the model, no matter how insignificant they are found to be. Those marked with REG_VAROUT will be excluded from of the model.

Setup up the regression the problem using the **StepwiseMulReg** constructor.

StepwiseMulReg constructor

Set up a stepwise multiple regression, including all of the independent variables in the final solution.

```
[Visual Basic]
Overloads Public Sub New(
   ByVal iv As DMatBase,
   ByVal dv As DMatBase
)
[C#]
public StepwiseMulReg(
   DMatBase iv,
   DMatBase dv
);
```

Set up a stepwise multiple regression, including only the independent variables flagged by the *consid* vector in the final solution.

```
[Visual Basic]
Overloads Public Sub New(
   ByVal iv As DMatBase,
   ByVal dv As DMatBase,
   ByVal consid As IVect
)
[C#]
public StepwiseMulReg(
   DMatBase iv,
   DMatBase dv,
   IVect consid
);
```

iv A matrix of the independent variable (x-values).
dv A matrix of the dependent variable (y-values).
consid A vector contains consideration values, one for each independent variable i the iv array, plus the constant. Element 0 contains the constant flag, the other elements contain the flags for the iv array. Initialize the array elements using one of the consider constants: REG_VARIN, REG_VAROUT, REG_VARCONSIDER. If an element is REG_VARIN it is always included in the final regression equation. If an element is REG_VAROUT it is excluded from the final regression equation. If an element is REG_VARCONSIDER, the corresponding variable available for selection into the final regression equation.

Backward Elimination

The backward elimination algorithm starts with a model that includes all of the variables marked with REG_VARIN and REG_VARCONSIDER. The basic algorithm is as follows:

Step 1. Solve for the current regression equation.

Step 2. Calculate the partial F statistic for every variable in the model.

Step 3. Find the variable with the smallest partial F statistic and using that value, compare the probability that the variable is significant to the value of the property **FToLeave**. If the probability that the variable is significant is less than **FToLeave**, the variable is removed from the model.

Step 4. Repeat, starting at Step 1, until the significance test in Step 3 finds no variable to remove. The current solution then becomes the final solution of the regression equation.

Method StepwiseMulReg.BackwardSolve

```
 [Visual Basic]
Overloads Public Function BackwardSolve( _
   ByVal regcoef As DDMat, _
   ByVal regstats As RegStats _
) As Integer

[C#]
public int BackwardSolve(
   DDMat regcoef,
   RegStats regstats
);
```

Parameters

regcoef Returns the calculated regression coefficients.

regstats Returns regression statistics. The **RegStats** class is a simple class that encapsulates several related summary statistics for multiple regression. See the description under the **MulReg** class section.

Forward Selection

The forward selection algorithm starts with a model that includes only the variables marked with REG_VARIN. If there are no variables marked with REG_VARIN, then the model starts with the variable that has the highest correlation with the dependent variable.

Step 1. Select the starting variable(s). This is either the variables marked with REG_VARIN, or the variable with the highest correlation with the dependent variable.

Step 2. Calculate the partial F statistic for every other variable marked with REG_VARCONSIDER.

Step 3. Find the variable with the largest partial F statistic and using that value, compare the probability that the variable is significant to the value of the property FToEnter. If

the probability that the variable is significant is greater than FToEnter, the variable is added to the model.

Step 4. Repeat, starting at Step 1, until the significance test in Step 3 finds no additional variables to add. The current solution then becomes the final solution of the regression equation.

Method StepwiseMulReg.ForwardSolve

```
 [Visual Basic]
Overloads Public Function ForwardSolve ( _
   ByVal regcoef As DDMat, _
   ByVal regstats As RegStats _
) As Integer

[C#]
public int ForwardSolve  (
   DDMat regcoef,
   RegStats regstats
);
```

Parameters

regcoef Returns the calculated regression coefficients.

regstats Returns regression statistics. The RegStats class is a simple class that encapsulates several related summary statistics for multiple regression. See the description under the MulReg class section

Stepwise Selection

The stepwise selection algorithm is similar to the forward selection algorithm, with an added step. After a variable is found significant and added to the model, the model is checked again to see if any of the partial F statistics fall below a predetermined minimum. In this case the variable is removed from the model. Variables might be removed in this fashion because of auto-correlation between other variables in the model.

Step 1. Select the starting variable(s). This is either the variables marked with REG_VARIN, or the variable with the highest correlation with the dependent variable.

Step 2. Calculate the partial F statistic for every other variable marked with REG_VARCONSIDER.

Step 3. Find the variable with the largest partial F statistic and using that value, compare the probability that the variable is significant to the value of the property FToEnter. If the probability that the variable is significant is greater than FToEnter, the variable is added to the model.

Step 4. Recalculate the model and find the variable with the smallest partial F statistic and using that value, compare the probability that the variable is significant to the value of the property FToLeave. If the probability that the variable is significant is less than FToLeave, the variable is removed from the model.

Step 5. Repeat, starting at Step 1, until the significance test in Step 3 finds no additional variables to add. The current solution then becomes the final solution of the regression equation.

Method StepwiseMulReg.StepwiseSolve

```
 [Visual Basic]
Overloads Public Function StepwiseSolve  ( _
   ByVal regcoef As DDMat, _
   ByVal regstats As RegStats _
) As Integer
```

```
[C#]
public int StepwiseSolve  (
   DDMat regcoef,
   RegStats regstats
);
```

Parameters

regcoef Returns the calculated regression coefficients.

regstats Returns regression statistics. The **RegStats** class is a simple class that encapsulates several related summary statistics for multiple regression. See the description under the **MulReg** class section

Examples for Stepwise Regression

The follow code fragments are extracted from the StepRegTest example program.

```
[C#]
StepwiseMulReg mulreg = new StepwiseMulReg ();
DDMat A = new DDMat(); // Independent variable matrix
DDMat RHS = new DDMat(); // Ddependent variable matrix
.
.
// Initialize A and RHS matrices;

mulreg = new StepwiseMulReg (A, RHS);
for (int i=0; i < mulreg.IndependentVariables.NumColumns + 1; i++)
    mulreg.SetConsider(i,MulReg.REG_VARIN);

RegStats regstats = new RegStats();
DDMat coefficients = new DDMat();
mulreg.Solve(coefficients, regstats);
regmode = GetRegMode();
switch (regmode)
{
```

```
    case 0:  mulreg.Solve(Coefficients, regstats ); break;
    case 1: mulreg.ForwardSolve(Coefficients, regstats );  break;
    case 2: mulreg.BackwardSolve(Coefficients, regstats );  break;
    case 3: mulreg.StepwiseSolve(Coefficients, regstats ); break;
   default:  mulreg.Solve(Coefficients, regstats ); break;
}


[VB]
Dim mulreg As New StepwiseMulReg()
Dim A As New DDMat() ' Independent variable matrix
Dim RHS As New DDMat() ' Ddependent variable matrix
.
.
.
mulreg = New StepwiseMulReg(A, RHS)
Dim i As Integer
For i = 0 To (mulreg.IndependentVariables.NumColumns + 1) - 1
   mulreg.SetConsider(i, MulReg.REG_VARIN)
Next i
Dim regstats As New RegStats()
Dim coefficients As New DDMat()
mulreg.Solve(coefficients, regstats)
regmode = GetRegMode()
Select Case regmode
   Case 0
      mulreg.Solve(Coefficients, regstats)
   Case 1
      mulreg.ForwardSolve(Coefficients, regstats)
   Case 2
      mulreg.BackwardSolve(Coefficients, regstats)
   Case 3
      mulreg.StepwiseSolve(Coefficients, regstats)
   Case Else
      mulreg.Solve(Coefficients, regstats)
End Select
```

Class SplitMulReg

What is the goal of your regression? If you want to find the best model that gives the smallest error for the existing data you should be using one of the stepwise multiple

regression algorithms. If you want to create a model that is the best predictor for new sample data, then you should try the **SplitMulReg** algorithm. This means that you are looking for a model that gives the best prediction of Y, given $X_1, X_2, \ldots X_k$ for some new observations.

The **SplitMulReg** algorithm is a modification of a stepwise regression that randomly assigns the raw sample data into two groups, a training group, and the holdout group. The original independent variables are replaced with their orthogonalized equivalents, so that inclusion of a new variable does not affect the coefficients for those already included in the model. At every step the independent variable with the smallest difference of coefficients determined independently on both data groups is chosen.

The algorithm does not involve the solution of a system of linear and is not sensitive to the colinearity of the independent variables. Depending on the data, the residual error on the original data may be higher than that using one of the other multiple regression algorithms, but the regression equation is usually more simple and reliable.

The **StepMulReg** class allows the programmer to include and exclude independent variables from the final regression equation using the consider (*consid*) parameter of the **StepMulReg** constructor. The selection mechanism will choose between variables marked REG_VARCONSIDER. Those marked with REG_VARIN will be included in the model, no matter how insignificant they are found to be. Those marked with REG_VAROUT will be excluded from of the model.

Setup up the regression the problem using the **SplitMulReg** constructor.

SplitMulReg constructor

Set up a split multiple regression, including all of the independent variables in the final solution.

```
[Visual Basic]
Overloads Public Sub New(
   ByVal iv As DMatBase,
   ByVal dv As DMatBase
)

[C#]
public SplitMulReg (
   DMatBase iv,
   DMatBase dv
);
```

Set up a split multiple regression, including only the independent variables flagged by the *consid* vector in the final solution.

```
[Visual Basic]
Overloads Public Sub New(
   ByVal iv As DMatBase,
   ByVal dv As DMatBase,
   ByVal consid As IVect
)
```

```
[C#]
public SplitMulReg (
   DMatBase iv,
   DMatBase dv,
   IVect consid
);
```

iv A matrix of the independent variable (x-values).
dv A matrix of the dependent variable (y-values).
consid A vector contains consideration values, one for each independent variable i the iv array, plus the constant. Element 0 contains the constant flag, the other elements contain the flags for the iv array. Initialize the array elements using one of the consider constants: REG_VARIN, REG_VAROUT, REG_VARCONSIDER. If an element is REG_VARIN it is always included in the final regression equation. If an element is REG_VAROUT it is excluded from the final regression equation. If an element is REG_VARCONSIDER, the corresponding variable available for selection into the final regression equation.

Use the **Solve** method to solve the current multiple regression using the current parameters. The methods returns the regression equation coefficients, and summary regression statistics.

Method SplitMulReg.Solve

```
 [Visual Basic]
Overloads Public Function Solve( _
   ByVal regcoef As DDMat, _
   ByVal regstats As RegStats _
) As Integer
```

```
[C#]
public int Solve(
   DDMat regcoef,
   RegStats regstats
);
```

Parameters

regcoef Returns the calculated regression coefficients.
regstats Returns regression statistics. The **RegStats** class is a simple class that encapsulates several related summary statistics for multiple regression:

8. Curve Fitting

CurveFit
CubicSplines

Experimental data often takes the form of measurements of some kind (temperature or volts for example) taken at discrete and possibly periodic times. In such cases a table of the measured variable versus time is produced. The goal of the research is to uncover the underlying function f(x), measured for the interval $[x_0..x_n]$. Once the underlying function is discovered (the solution is usually only an approximation of the true function), the function can be used to calculate the values of f(x) (temperature in this case) for x values (points in time) which were not part of the original measured data. Polynomials are generally used as approximating functions because of their simplicity and speed of calculation on computers. There are several ways to use polynomials to approximate a discrete function. The first is to fit a single polynomial to a group of data points. This is called *polynomial curve fitting* and that is what our **CurveFit** class does. The second method starts with the assumption that the curve between each contiguous pair of data points is best modeled using a unique cubic (polynomial of degree 3) equation. This is called *cubic splines* and that is what our **CubicSplines** class does.

Polynomial Curve Fitting

Polynomial curve fitting results in a single polynomial equation of order *n* which is the least squares approximation of the original data.

Eqn. 1 $$Y = C_0 + C_1 * X^1 + C_2 * X^2 + C_3 * X^3 + ... C_n * X^n$$

Predict what the value of Y will be for a given X by plugging a value for X into the equation and solving it for Y. One of the most common applications of polynomial curve fitting is thermocouple linearization where the voltage present at a thermocouple junction is transformed into temperature by applying a polynomial equation which has been solved for using these types of curve fitting techniques.

Polynomial curve fitting is actually a special case of least squares multiple regression. Eqn. 1 above is transformed into the standard multiple regression equation:

Eqn. 2 $$Y = C_0 + C_1 * X_1 + C_2 * X_2 + C_3 * X_3 + ... C_n * X_n$$

using the transforms:

$X_1 = X$

$X_2 = X^2$

$X_3 = X^3$

.

.

.

$X_n = X^n$

A system with one dependent variable Y and one independent variable X is turned into a system of one dependent variable Y and as many independent variables (X_1, X_2 ...X_n) as the order of the curve fit. Each new independent variable is the original independent variable raised to some power. Once the transform is carried out, the multiple regression function is called to calculate the solution coefficients C_0 through C_n. One of the most important measures of the quality of the polynomial fit is known as the correlation coefficient. The correlation coefficient is usually abbreviated as the r-value (R) of the fit. The closer this value is to 1, the better the fit. Another measure of the fit is called the coefficient of determination, usually referred to as the r-squared (R^2) value. This value is equal to the square of the correlation coefficient. Again, the closer this value is to 1, the better the fit. The standard error of the estimate (usually abbreviated SEE), is yet another measure of the quality of the fit. It is a measure of the scatter of the actual data about the fitted line. The smaller the SEE value, the closer the actual data is to the theoretical polynomial equation. Other equations, such as rational functions, exponentials, etc. also can be used for curve fitting. These functions are handled in a manner analogous to polynomial curve fitting. The original data is transformed in a manner which reduces a non-linear curve fitting problem into linear curve fitting problem which can be solved using linear multiple regression.

Class CurveFit

The **CurveFit** class will fit a polynomial equation to a set of data representing discrete samples of some function y = f(x). It can also fit exponential, rational polynomial and mixed equation to the same data. A polynomial curve fit is represented by the equation:

$y = f(x) \rightarrow \quad y = a_0 + a_1 * x^1 + a_2 * x^2 + a_3 * x^3 + ... a_n * x^n$

The polynomial curve fit algorithm solves for the coefficients a_0 to a_n.

An exponential curve fit is represented by the equation:

$y = f(x) \rightarrow y = ae^{bx}$

The exponential curve fit algorithm solves for the coefficients a and b. The rational polynomial is represented by the equation:

$$y = f(x) \rightarrow y = \frac{a_0 + a_1 * x^1 + a_2 * x^2 + a_3 * x^3 + ... a_n * x^n}{1 + b_1 * x^1 + b_2 * x^2 + b_3 * x^3 + ... b_n * x^n}$$

The rational polynomial curve fit algorithm solves for the coefficients a_0 to a_n and b_1 to b_n.

The mixed fit curve fit algorithm solves for a linear combination of the polynomial, exponential, and rational polynomial curve fits, represented using the equation:

$$y = f(x) \rightarrow y = a_0 + a_1 * x^1 + a_2 * x^2 + a_3 * x^3 + ... a_n * x^n + b_1/x^1 + b_2/x^2 \ ... \ b_n / x^n + c * \ln(x).$$

CurveFit constructor

```
 [Visual Basic]
Overloads Public Sub New( _
   ByVal iv As DMatBase, _
   ByVal dv As DMatBase _
)

[C#]
public CurveFit(
   DMatBase iv,
   DMatBase dv
);
```

iv A vector of the independent variable (x-values).
dv A vector of the dependent variable (y-values).

The four curve fit algorithms all use the constructor above. Call the solve method appropriate to the algorithm you want to use.

Method CurveFit.PolynomialSolve

This method fits the data to a polynomial equation of the form:

$$y = a_0 + a_1 * x^1 + a_2 * x^2 + a_3 * x^3 + ... a_n * x^n$$

where *n* is considered the order of the polynomial. The **PolynomialSolve** method returns the solution coefficients of the polynomial ($a_0 \ldots a_n$) summary statistics for the curve fit.

```
[Visual Basic]
 Public Function PolynomialSolve( _
   ByVal order As Integer, _
   ByVal regcoef As DDMat, _
   ByVal regstats As RegStats _
) As Integer

[C#]
public int PolynomialSolve(
   int order,
   DDMat regcoef,
   RegStats regstats
);
```

Parameters

order Set the maximum order of the polynomial.
regcoef Returns the calculated curve fit coefficients. The coefficients are returned in an array, elements [0] to [order].
regstats Returns curve fit statistics.

Return Value

Returns an error code.

RegStats class

Public Instance Properties

Ovfst	Get/Set overall F statistic
R	Get/Set multiple correlation coefficient (R-value)
Rsq	Get/Set coefficient of determination (R-Squared)
See	Get/Set Returns the Standard error of estimate (
Sigflag	Get/Set significance of regression flag
Sumressq	Get/Set sum of residuals squared

Method CurveFit.ExponentialSolve

This method fits the data to an exponential equation of the form:

$$y = ae^{bx}.$$

The **ExponentialSolve** method returns the solution coefficients *a* and *b* in the equation above. All values of y must be positive.

```
[Visual Basic]
 Public Function ExponentialSolve( _
   ByVal regcoef As DDMat, _
   ByVal regstats As RegStats _
) As Integer
```

```
[C#]
public int ExponentialSolve (
   DDMat regcoef,
   RegStats regstats
);
```

Parameters

regcoef Returns the calculated curve fit coefficients. The (a) coefficient is returned in the array element [0] and the (b) coefficient is returned in the array element [1].

regstats Returns curve fit statistics. The **RegStats** class is described under the **CurveFit.PolynomialSolve** section.

Return Value

Returns an error code.

Method CurveFit.RationalSolve

This method fits the data to a rational polynomial equation of the form:

$$y = \frac{a_0 + a_1 * x^1 + a_2 * x^2 + a_3 * x^3 + ... a_n * x^n}{1 + b_1 * x^1 + b_2 * x^2 + b_3 * x^3 + ... b_n * x^n}$$

The **RationalSolve** method returns the solution coefficients a_0 … a_n and $b_1 + b_n$ in the equation above.

```
[Visual Basic]
Overloads Public Function RationalSolve( _
   ByVal order As Integer, _
   ByVal regcoef As DDMat, _
   ByVal regstats As RegStats _
) As Integer
```

```
[C#]
public int RationalSolve(
   int order,
   DDMat regcoef,
   RegStats regstats
);
```

Parameters

order Set the maximum order of the polynomial.

regcoef Returns the calculated curve fit coefficients. The (a) coefficients are returned in array element [0..order] and the (b) coefficients are returned in array elements [order+1..2 * order].

regstats Returns curve fit statistics. The **RegStats** class is described under the **CurveFit.PolynomialSolve** section.

Return Value

Returns an error code.

Method CurveFit.MixedSolve

This method fits the data to a mixed polynomial equation of the form:

$$y = a_0 + a_1 * x^1 + a_2 * x^2 + a_3 * x^3 + ... a_n * x^n +$$

$$b_1 / x^1 + b_2 / x^2 \ ... \ b_n / x^n +$$

$$c * \ln(x).$$

The **MixedSolve** method returns the solution coefficients $a_0 \ldots a_n$, $b_1 + b_n$, and c in the equation above.

```
[Visual Basic]
Overloads Public Function MixedSolve( _
   ByVal order As Integer, _
   ByVal regcoef As DDMat, _
   ByVal regstats As RegStats _
) As Integer
```

```
[C#]
public int MixedSolve(
   int order,
   DDMat regcoef,
   RegStats regstats
);
```

Parameters

order Set the maximum order of the polynomials.

regcoef Returns the calculated curve fit coefficients. The (a) coefficients are returned in array element [0..order], the (b) coefficients are returned in array elements [order+1..2 * order], and c is returned in element [2 * order + 1].

regstats Returns curve fit statistics. The **RegStats** class is described under the **CurveFit.PolynomialSolve** section.

Return Value

Returns an error code.

Curve fitting example – Extracted from the example program CurveFitTest.

```
[C#]

CurveFit curvefit = null;
int numObs = 100;
int simOrder  = 6;
int solveOrder  = 3;
int cftype = 0;
double simErr = 0.1;
DDMat A = new DDMat(); // Independent variable matrix
DDMat RHS = new DDMat(); // Dependent variable matrix
DDMat Coefficients = new DDMat();
DDMat fstats = null;
DDMat coefdev = null;
RegStats regstats = new RegStats();
.
.  // Initialize data
.
curvefit = new CurveFit(A, RHS);

cftype = GetCurveFitAlgorithm();
switch (cftype)
{
    case 1: curvefit.PolynomialSolve(solveOrder, Coefficients, regstats); break;
    case 2: curvefit.ExponentialSolve( Coefficients, regstats); break;
    case 3: curvefit.RationalSolve(solveOrder, Coefficients, regstats); break;
    case 4: curvefit.MixedSolve(solveOrder, Coefficients, regstats); break;
    default: curvefit.PolynomialSolve(solveOrder, Coefficients, regstats); break;
}

fstats = curvefit.FStats;
coefdev = curvefit.CoefficientDev;


[VB]
Dim curvefit As curvefit = Nothing
Dim numObs As Integer = 100
Dim simOrder As Integer = 6
Dim solveOrder As Integer = 3
Dim cftype As Integer = 0
Dim simErr As Double = 0.1
```

```
Dim A As New DDMat() ' Independent variable matrix
Dim RHS As New DDMat() ' Ddependent variable matrix
Dim Coefficients As New DDMat()
Dim fstats As DDMat = Nothing
Dim coefdev As DDMat = Nothing
Dim regstats As New regstats()

solveOrder = GetSolveOrder()
curvefit = New CurveFit(A, RHS)
cftype = GetCurveFitAlgorithm()
Select Case cftype
   Case 1
     curvefit.PolynomialSolve(solveOrder, Coefficients, regstats)
   Case 2
     curvefit.ExponentialSolve(Coefficients, regstats)
   Case 3
     curvefit.RationalSolve(solveOrder, Coefficients, regstats)
   Case 4
     curvefit.MixedSolve(solveOrder, Coefficients, regstats)
   Case Else
     curvefit.PolynomialSolve(solveOrder, Coefficients, regstats)
 End Select

fstats = curvefit.FStats
coefdev = curvefit.CoefficientDev
```

Cubic Splines

The cubic splines algorithm starts with the assumption that the curve between each contiguous pair of data points

(x_0, y_0)-(x_1,y_1)

(x_1, y_1)-(x_2,y_2)

(x_2, y_2)-(x_3,y_3)

.

.

(x_{n-1}, y_{n-1})-(x_n,y_n)

is best modeled using a unique cubic (polynomial of degree 3) equation. If you start with (0..n) data points (for a total of n+1 data points), you end up with *n* cubic equations, one for each segment between the data points. These cubic equations are used interpolate an estimate for f(x), for any x, in the interval $[x_0..x_n]$. Additional constraints force continuity between the first and second derivatives for each curve as you pass from one segment to the next, within the interval $[x_0..x_n]$. The continuity of the derivatives is what gives the resulting curve a smooth look analogous to the wooden *spline* that was once used by draughtmen to draw a smooth line through a series of points defining a curve.

The cubic splines algorithm implementation creates a set of equations, (n-1 x n-1), based on the constraints that the y-value, and the first and second derivatives at each of the interior nodes, must match for each interval in the range $[x_0..x_n]$. Because each segment is only linked to its nearest neighbors, the resulting system of equations is tridiagonal. A tridiagonal system of equations can be solved using a specialized algorithm that is orders of magnitudes faster than generalized methods such as Gauss-Jordan and LU decomposition. The solution is used to created the table (n x 4) of cubic equation coefficients that are used to interpolate the f(x) values for x in the range $[x_0..x_n]$.

Cubic splines has several limitation that you must be aware of before using it.

- The raw data must be monotonic in x. This means that the data must be sorted in increasing order by x and that the x-values must always be increasing. You cannot have exactly the same x-value repeated twice.

- The data cannot reflect a function that has a discontinuous first or second derivative. A good example of a discontinuous second derivative is a step change in the function. This also violates the previous limitation, since in order to implement a true step change, a given f(x) value is associated with two x values. For example, the line segments represented by the data points:

  Point 1 (0,0)

  Point 2 (1,0)

  Point 3 (1,1)

  Point 4 (2,1)

  exhibit a discontinuity between points 2 and 3, where a step change occurs and the second derivative becomes infinite. If you are close to a step change, the cubic splines algorithm my produce while swings around in the evaluated function in the transition area.

- Cubic splines can only be used to interpolate data points in the original, fitted data interval defined by $[x_0..x_n]$. If you attempt to calculate an f(x) value outside of the interval, the algorithm will use the cubic equation of the nearest segment, either the $[x_0 ..x_1]$ or the $[x_{n-1} ..x_n]$ segment. This can result in wild swings that are not an accurate representation of the underlying function.

- The second derivative of the function is assumed to be 0 at the endpoints x_0 and x_n. This is known as a natural spline because it assumes the shape that a wooden spline would take if the ends were left free.

Class CubicSplines

The **CubicSplines** class calculates the table of cubic spline equations used in interpolating values within the range of the original data.

CubicSplines constructor

```
 [Visual Basic]
Overloads Public Sub New( _
   ByVal x As DDMat, _
   ByVal y As DDMat _
)
[C#]
public CubicSplines(
   DDMat x,
   DDMat y
);
```

Parameters

x A matrix of the independent variable (x-values).
y A matrix of the dependent variable (y-values).

CubicSplines.InterpolatePoint Method

Interpolate a new y-value given an x-value and the previously calculated spline coefficients.

```
[Visual Basic]
Public Function InterpolatePoint( _
   ByVal x As Double _
) As Double
[C#]
public double InterpolatePoint(
   double x
);
```

Parameters

x The x-value to interpolate a new y-value for.

Return Value

Returns the interpolated y-value.

Cubic splines example – Extracted from the example program CubicSplinesTest.

```
[C#]
CubicSplines csplines;
int sampleN = 21;
// Define sampled data points
DDMat dataY;
DDMat dataX;

// Original x- data goes from 0 - 20, so interpolated must be in same range
int interpolatedN = 201;
// Interpolated points
DDMat interpolateY;
DDMat interpolateX ;
void SetupCubicSplines()
{
    dataY = new DDMat(sampleN);
    dataX = new DDMat(sampleN);
    for (int i=0; i < sampleN; i++)
    {
        double x = (double) i/ 2.0;
        dataX[i] = x;
        dataY[i] = 3.5 * Math.Cos(x);
    }

.
.
.
    csplines = new CubicSplines(dataX, dataY);
}

void InterpolatePoints()
{
    interpolateY = new DDMat(interpolatedN);
    interpolateX = new DDMat(interpolatedN);
    actualY = new DDMat(interpolatedN);
    residualY = new DDMat(interpolatedN);
```

```
    // This interpolates on the same iterval as the original data
    for (int i=0; i < interpolatedN; i++)
    {
        double x =  (double) i/ 20.0;
        interpolateX[i] = x;
        interpolateY[i] = csplines.InterpolatePoint(x);
        actualY[i] = 3.5 * Math.Cos(x);
        residualY[i] = interpolateY[i] - actualY[i];
    }
    .
    .
    .
}

[VB]
Dim csplines As CubicSplines

Dim sampleN As Integer = 21
' Define sampled data points
Dim dataY As DDMat
Dim dataX As DDMat

' Original x- data goes from 0 - 20, so interpolated must be in same range
Dim interpolatedN As Integer = 201
' Interpolated points
Dim interpolateY As DDMat
Dim interpolateX As DDMat

' actual points
Dim actualY As DDMat

' Residual values
Dim residualY As DDMat

Sub SetupCubicSplines()
    dataY = New DDMat(sampleN)
    dataX = New DDMat(sampleN)
    Dim i As Integer
    For i = 0 To sampleN - 1
        Dim x As Double = CDbl(i) / 2.0
        dataX(i) = x
        dataY(i) = 3.5 * Math.Cos(x)
    Next i
```

```
    .
    .
    .
    csplines = New CubicSplines(dataX, dataY)
End Sub 'SetupCubicSplines


Sub InterpolatePoints()
    interpolateY = New DDMat(interpolatedN)
    interpolateX = New DDMat(interpolatedN)
    actualY = New DDMat(interpolatedN)
    residualY = New DDMat(interpolatedN)
    .
    .
    .
    ' This interpolates on the same iterval as the original data
    Dim i As Integer
    For i = 0 To interpolatedN - 1
       Dim x As Double = CDbl(i) / 20.0
       interpolateX(i) = x
       interpolateY(i) = csplines.InterpolatePoint(x)
       actualY(i) = 3.5 * Math.Cos(x)
       residualY(i) = interpolateY(i) - actualY(i)
    Next i
    .
    .
    .
End Sub 'InterpolatePoints
```

9. Digital Signal Processing

DSP

FFT Basics

A large class of numerical analysis tools involves use of Fourier analysis. Applications for the Fourier transform include speech, image, radar, and general signal processing. Implementations of the Fourier transform using sampled data on computers are generally referred to as DFT (Discrete Fourier Transform). The equation below computes the DFT, (X_k), of the input signal, x_n.

$$X_k = \sum_{n=0}^{N-1} x_n e^{-\frac{2\pi i}{N} kn} \qquad k = 0, \ldots, N-1$$

A complex summation of N complex multiplications is required for each of N samples. This adds up to N^2 complex multiplications and N^2 complex additions to compute an N point DFT. A 1024 point DFT calculated using the equation above would require 4 million floating point multiplications and 4 million floating point additions. In the early 1960's researchers (notably Cooley and Tukey) noticed patterns in the DFT calculation that, when exploited properly, could be used to reduce the number of complex multiplications to $N * \text{Log}_2 N$. The number of floating point multiplications in a 1024 point DFT is reduced by 99%, to 40,000. The entire class of Fast DFT algorithms is known as FFT (Fast Fourier Transform).

As a historical note, while Cooley and Tukey are usually given credit for the invention of FFT, based on the publication of their algorithm in 1965, it is now known that the German mathematician Carl Frederick Gauss invented a near identical version of the FFT in the early 1800's. He used it as an aid in calculating the trajectories of asteroids and planets. Between 1800 and 1965 the FFT algorithm has been "re-invented" a number of times.

FFT Harmonics

The underlying assumption of an FFT is that an arbitrary, sampled signal can be recreated as a summation of other periodic waveforms. The FFT functions will calculate the periodic waveforms that sum up to make the original signal. The FFT functions give you enough information to calculate the frequency, magnitude and phase shift of each harmonic component. The frequency of the harmonic components in the final answer depends on the sample rate used when sampling the original, raw waveform. The FFT

can only return frequencies that are simple integer fractions of the original sampling frequency (sample frequency = SF). The range of frequencies will range from 0 (DC level or average value of the signal) to SF/2 (or the Nyquist frequency for the sample rate of SF). For example, assume that 16 samples of a periodic signal are taken at a rate of 480 Hz. The FFT algorithm will calculate the degree to which the following frequencies contribute to the signal makeup.

Harmonic	**Frequency**
0	(0/16) * 480 = 0 Hz = DC level
1	(1/16) * 480 = 30 Hz
2	(2/16) * 480 = 60 Hz
3	(3/16) * 480 = 90 Hz
4	(4/16) * 480 = 120 Hz
5	(5/16) * 480 = 150 Hz
6	(6/16) * 480 = 180 Hz
7	(7/16) * 480 = 210 Hz
8	(8/16) * 480 = 240 Hz

If you were interested in the degree to which 60 Hz (AC line frequency) noise was affecting your signal, then you could concentrate on harmonic #2 which in the example above is at 60 Hz. The general equation for calculating the frequency for a given harmonic index is:

$$F = (H/N) * SF$$

where F = frequency of harmonic H,
H = harmonic index (range 0 to N/2),
N = number of sampled data points,
SF = sample frequency.

Assume that you are sampling waveform at 50KHz and you want to resolve individual frequency components down as low as 8 Hz. How many data points do you need to sample? The formula becomes:

$$8\ Hz = (1 / N) * 50KHz, \quad \text{or}$$
$$N = (1/8) * 50KHz = 6250$$

The FFT algorithms in this package require a number of data points that is a power of 2. You should round the result to the next power of 2 above the calculated value, or 8192. The first harmonic of this sampled waveform becomes (1/8196) * 50KHz, or 6.1 Hz, that is as close as you can get to the original 8 Hz requirement without changing the sample rate.

The FFT routines use the original waveform as input. This is passed to the function as an array (vector or pointer) of floating point numbers. The output of the FFT function is one

complex number (a + b *i*) for each harmonic component in the original waveform. The output is passed back as two arrays one of which holds real parts of the complex numbers and another - imaginary parts.

The input to the FFT can be an array of real or complex numbers *(* a + b *i*). Calculate an N point complex FFT, and the primary results are returned in the first N/2 elements of the real and imaginary arrays. These elements hold the harmonic values for the positive frequencies that make up the waveform. The last half of the arrays hold the harmonic values for the negative frequencies that make up the waveform. The negative frequencies are symmetrical to the positive frequencies about the folding frequency of the harmonic (N/2). The folding frequency represented by the harmonic N/2 is also the Nyquist sample frequency for the original signal. Continuing a previous example, assume that 16 points of a signal are sampled at a rate of 480 Hz. The sampled waveform is contained in the array *w*.

w = (6.0, 1.85, -2.59, 0.765, 4.0, -0.765, -5.41, -1.85, -2.0, -1.85, -5.41, -0.765, 4.0, 0.765, -2.59, 1.85)

The FFT function returns a complex number for each positive and negative harmonic in the waveform. Assume that the real parts are returned in the vector *va* and the imaginary parts in vector *vb*. The complex number representing the value for harmonic #3 would be *va*[3] + *vb*[3] i. The complex number for the highest harmonic in a 16 point FFT would be *va*[8] + *vb*[8]i.

Many questions arise regarding interpretation of the FFT results. The absolute values of a FFT are proportional to the number of data points used in the calculation. Some FFT routines normalize the results of the FFT by dividing the calculated values by N or N/2, while the majority do not. We do not normalize the results because this would make our algorithms different from the majority of popular FFT algorithms described in the literature. This can be confusing to people who have never calculated an FFT before. If you are looking for the relative magnitude of one harmonic versus the other you can ignore the normalization factor. If you need to recover the exact value of a given harmonic, normalize the results of the FFT by N/2 if you intend to use the positive harmonics, and N if you plan to use both positive and negative harmonics. The frequency, magnitude and phase shift for each harmonic index are calculated according to the formulas below. It is assumed that results of the FFT have been returned in vector's *va* (real parts) and *vb* (imaginary parts).

DSP Windowing

Windowing functions are frequently used in digital signal processing**.** One of the common applications is to reduce the undesirable effects related to spectral leakage. Spectral leakage is the result of discontinuities in the sampled waveform. Since the waveform is sampled for a finite length of time, discontinuities occur at the end points of the waveform. Windows are weighting functions applied to the raw data to reduce the spectral leakage associated with the finite observation interval**.** A window function typically multiplies the data in the sample interval by a function which has a value of one

at its center and tapers to zero (or near zero) at both end points. The most common DSP windows are:

High and moderate resolution windows

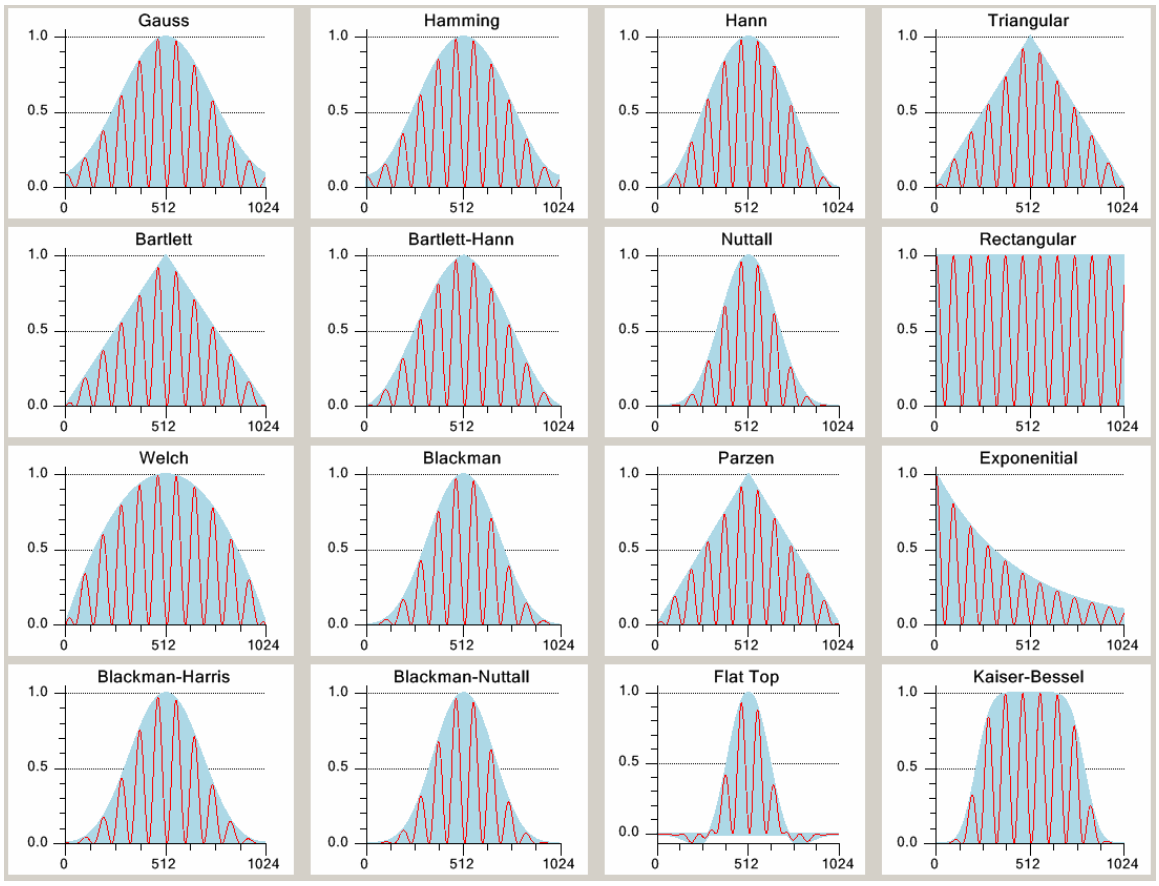
Rectangular	Gauss	Parzen	Welch
Hann (Hanning)	Hamming	Bartlett	Triangular
Bartlett-Hann	Blackman		

Low dynamic range (low resolution) windows

Nuttall	Blackman–Harris	Blackman–Nuttall	Flat top

Other

Exponential	Kaiser-Bessel



You can also apply your own custom window to the raw data. Just apply your windowing function to the raw data, and call the **FFTCalc** method that does not use a windows parameter. Or you can call the **FFTCalc** method that does specify a window parameter, and in that case specify DPS.DSPWIN.NOWIN window, since that passes through the raw data without modification.

Class DSP

The source data for an FFT can take real-only, or complex form. The raw data can be passed to the **DSP** class as simple double arrays, or as **DDMat** and **DXMat** array classes.

DSP constructor

Create a **DSP** object using double arrays.

```
[Visual Basic]
Overloads Public Sub New( _
   ByVal re As Double(), _
   ByVal imag As Double() _
)

[C#]
public DSP(
   double[] re,
   double[] imag
);
```

re Array of real values of the raw data.
imag Array of imaginary values of the raw data. This parameter can be null for a FFT that starts with real data.

DSP constructor where the raw data is real-only and passed in using a **DDMat** matrix object.

```
[Visual Basic]
Overloads Public Sub New( _
   ByVal source As DDMat _
)

[C#]
public DSP(
   DDMat source
);
```

Parameters

source
Source vector of fft real data.

DSP constructor where the raw data is complex and passed in using a DXMat matrix.

```
[Visual Basic]
Overloads Public Sub New( _
```

```
   ByVal source As DXMat _
)
[C#]
public DSP(
   DXMat source
);
```

Parameters

source Source vector of fft complex data.

The constructors do not calculated the FFT. They just store the raw data. Calculate the actual FFT using one of the following **FFTCalc** methods.

Method DSP.FFTCalc

Calculate the forward or inverse FFT of the raw data. If the original data is real-only (no imaginary component) a real-only version of the FFT algorithm is called. If the original data is complex, a complex version of the FFT algorithm is called.

```
[Visual Basic]
Overloads Public Function FFTCalc( _
   ByVal bInverse As Boolean _
) As DXMat
[C#]
public DXMat FFTCalc(
   bool bInverse
);
```

Apply a FFT window to the raw data and then calculate the forward or inverse FFT of the raw data.

```
[Visual Basic]
Overloads Public Function FFTCalc( _
   ByVal bInverse As Boolean, _
   ByVal fftwin As DSPWIN _
) As DXMat
[C#]
public DXMat FFTCalc(
   bool bInverse,
   DSPWIN fftwin
);
```

Parameters

bInverse Set to true and an inverse FFT is calculated.

fftwin DSP window type. Use one of the DSPWIN enumerated constants: NOWIN, RECTANGULAR, GAUSS, HAMMING, HANN, BARTLETT, BARTLETT_HANN, NUTTALL, BLACKMAN_HARRIS,

BLACKMAN_NUTTALL, FLATTOP, PARZEN, WELCH, BLACKMAN, and TRIANGULAR, KAISER_BESSEL and EXPONENTIAL.

Return Value

Returns the FFT of the raw data as a DXMat matrix.

A few of the windows have additional parameters that you may want to change. Set the Gauss window sigma parameter using the **DSP.GaussSigma** static property. Set the Exponential window final value parameter using the **DPS.ExpFinalValue** value static property. Set the Kaiser-Bessel window alpha parameter using the **DSP.KBAlphaValue** static property.

```
// Default values
DSP.GuassSigma = 0.45;
DSP.ExpFinalValue = 0.1;
DSP.KBAlphaValue = 1;
```

Example (Extracted from the example FFTTest)

```
[C#]
int n = 4096;
double [] xR = new double[n];
double [] iR = new double[n];
for (int i=0; i < n; i++)
{
    double f = 10.0 * Math.PI * 2 * ((double) i/ (double) n);
    xR[i] = 13*Math.Cos(f) + 31*Math.Cos(f*2);
    // Add in a fixed offset and Randomize it a bit
    xR[i] += 4.0 + (0.5 - DMatBase.GetRandomDouble());
    iR[i] = 0;
}

DDMat origData = new DDMat(xR);
DXMat FFTResult = new DXMat();

// Since iR[i] is all zeros, can use real only version of DSP
DSP fftobj = new DSP(origData);
FFTResult = fftobj.FFTCalc(false);

[VB]
Dim n As Integer = 4096
' MUST use n-1 because VB arrays are dimension from 0 to N, not 0 to N-1
Dim xR(n - 1) As Double
```

```
Dim iR(n - 1) As Double

Dim i As Integer
For i = 0 To n - 1
  Dim f As Double = 10.0 * Math.PI * 2 * (CDbl(i) / CDbl(n))
  xR(i) = 13 * Math.Cos(f) + 31 * Math.Cos((f * 2))
  ' Add in a fixed offset and Randomize it a bit
  xR(i) += 4.0 + (0.5 - DMatBase.GetRandomDouble())
  iR(i) = 0
Next i

' Since iR[i] is all zeros, can use real only version of FFT
Dim origData As New DDMat(xR)

Dim FFTResult As New DXMat()
' Results are returned in source arrays xR and iR
Dim fftobj As New DSP(origData)
' Results are complex numbers, so use DXMat
FFTResult = fftobj.FFTCalc(False)
```

Method DSP.FFTMagnitude

Calculates the FFT magnitude associated with a given harmonic index.

```
[Visual Basic]
Overloads Public Shared Function FFTMagnitude( _
   ByVal source As XMatBase, _
   ByVal i As Integer _
) As Double
[C#]
public static double FFTMagnitude(
   XMatBase source,
   int i
);
```

Parameters

source Source vector contains the results of an FFT calculation.
i The index of the harmonic you are calculating the magnitude for.

Return Value

Returns the FFT magnitude associated with a given harmonic index.

Example

```
[C#]
```

```
DDMat magdata = new DDMat(FFTResult.Length);
for (int i=0; i < FFTResult.Length; i++)
        magdata[i] = DSP.FFTMagnitude(FFTResult, i);
[VB]
Dim magdata As New DDMat(FFTResult.Length)
Dim i As Integer
For i = 0 To FFTResult.Length - 1
   magdata(i) = DSP.FFTMagnitude(FFTResult, i)
Next i
```

Calculate all of the FFT magnitudes associated with an FFT results matrix.

```
[Visual Basic]
Overloads Public Shared Function FFTMagnitude( _
   ByVal source As XMatBase _
) As DDMat
[C#]
public static DDMat FFTMagnitude(
   XMatBase source
);
```

Parameters

source Source vector contains the results of an FFT calculation.

Return Value

Returns a **DDMat** matrix of the FFT magnitudes associated with the FFT data.

Example (Extracted from the example FFTTest)

```
DDMat magdata = DSP.FFTMagnitude(FFTResult);
```

Method DSP.FFTPhase

Calculates the FFT phase associated with a given harmonic index.

```
[Visual Basic]
Overloads Public Shared Function FFTPhase( _
   ByVal source As XMatBase, _
   ByVal i As Integer _
) As Double
[C#]
public static double FFTPhase(
   XMatBase source,
   int i
);
```

Parameters

source Source vector contains the results of an FFT calculation.
i The index of the harmonic you are calculating the phase for.

Return Value

Returns the FFT phase associated with a given harmonic index

Example

```
[C#]
DDMat phasedata = new DDMat(FFTResult.Length);
for (int i=0; i < FFTResult.Length; i++)
        pasedata[i] = DSP.FFTPhase(FFTResult, i);


[VB]
Dim phasedata As New DDMat(FFTResult.Length)
Dim i As Integer
For i = 0 To FFTResult.Length - 1
   pasedata(i) = DSP.FFTPhase(FFTResult, i)
Next i
```

Method DSP.FFTPhase2

Calculates the FFT phases associated with already calculated fft data.

```
[Visual Basic]
Overloads Public Shared Function FFTPhase2( _
   ByVal source As XMatBase _
) As DMatBase
[C#]
public static DMatBase FFTPhase2(
   XMatBase source
);
```

Parameters

source Source vector contains the results of an FFT calculation.

Return Value

Returns a **DDMat** matrix of the fft phases associated with the fft data.

Example (Extracted from the example FFTTest)

```
[C#]
DDMat phasedata = DSP.FFTPhase2(FFTResult);


[VB]
```

```
Dim phasedata As DDMat = DSP.FFTPhase2(FFTResult)
```

Method DSP.FFTFrequency2

Calculates the FFT frequencies associated with already calculated FFT data.

```
[Visual Basic]
Public Shared Function FFTFrequency2( _
   ByVal lNumdat As Integer, _
   ByVal rSampleFreq As Double _
) As DDMat

[C#]
public static DDMat FFTFrequency2(
   int lNumdat,
   double rSampleFreq
);
```

Parameters

lNumdat The number of data points, must be a power of 2.
rSampleFreq The sample frequency of the raw data.

Return Value

Returns a matrix of the FFT frequencies associated with the FFT data.

Example (Extracted from the example FFTTest)

```
[C#]

DDMat freqdata = DSP.FFTFrequency2(FFTResult.Length, 1000.0);


[VB]

Dim freqdata As DDMat = DSP.FFTFrequency2(FFTResult.Length, 1000.0)
```

Power Spectrum Calculations

This function calculates the power spectrum periodogram of a sampled data set. The power spectral density of each frequency bin is returned, along with the exact frequency in Hz for each frequency bin.

Method: If N data points of a waveform $w(t)$ are collected at equal intervals, then the FFT of the waveform can be denoted as $W(t)$. The periodogram estimate of the power spectrum, $P(k)$ is defined as:

$$P_0 = \frac{1}{N^2}\left|W_0\right|^2$$

$$P_0 = \frac{1}{N^2}\left[\left|W_k\right|^2 + \left|W_{N-k}\right|^2\right]_{k = 1, 2, \ldots, (N/2 - 1)}$$

$$P_{\frac{N}{2}} = \frac{1}{N^2}\left|W_{\frac{N}{2}}\right|^2$$

where *k* is defined for zero and positive frequencies.

Method DSP.PowerSpectrumCalc

Calculates the power spectrum periodogram of a sampled dataset.

```
[Visual Basic]
Overloads Public Shared Function PowerSpectrum( _
   ByVal source As XMatBase, _
   ByVal rInterval As Double, _
   ByVal freqvalues As DDMat _
) As DDMat

[C#]
public static DDMat PowerSpectrum(
   XMatBase source,
   double rInterval,
   DDMat freqvalues
```

Real-only version of the power spectrum periodogram of a sampled dataset

```
[Visual Basic]
Overloads Public Shared Function PowerSpectrum( _
   ByVal source As DDMat, _
   ByVal rInterval As Double, _
   ByVal freqvalues As DDMat _
) As DDMat

[C#]
public static DDMat PowerSpectrum(
   DDMat source,
   double rInterval,
   DDMat freqvalues
);
```

Parameters

source	Raw data. The power spectrum routine takes the FFT of the data, pass in raw data.
rInterval	The sample period between adjacent data points in the seconds.
freqvalues	Returns the frequency values associated with each harmonic index.

Return Value

Returns the power spectrum of the original signal.

Example (Extracted from the example FFTTest)

```
[C#]
int n = 4096;
double [] xR = new double[n];
double [] iR = new double[n];
for (int i=0; i < n; i++)
{
  .
  .
  .
}

DDMat origData = new DDMat(xR);

// Since iR[i] is all zeros, can use real only version of DSP
DSP fftobj = new DSP(origData);
DDMat freqdata = new DDMat();
//This routine takes the raw data, pre-RealFFT
// sample interval for 1000.0 Hz is 0.001 seconds
DDMat powerSpectrum = fftobj.PowerSpectrum( 0.001, freqdata);

[VB]

Dim n As Integer = 4096
' MUST use n-1 because VB arrays are dimension from 0 to N, not 0 to N-1

Dim xR(n-1) As Double
Dim iR(n-1) As Double
Dim i As Integer
For i = 0 To n - 1
.
.
.
Next i


Dim origData As New DDMat(xR)
```

```
' Since iR[i] is all zeros, can use real only version of DSP
Dim fftobj As New DSP(origData)
Dim freqdata As New DDMat()
'This routine takes the raw data, pre-RealFFT
' sample interval for 1000.0 Hz is 0.001 seconds
Dim powerSpectrum As DDMat = fftobj.PowerSpectrum(0.001, freqdata)
```

10. Matrix Viewers

com.quinncurtis.matviewnet.MatViewer
MatViewerBase
DMatViewer
XMatViewer

The QCMatViewNet DLL contains a couple of simple .Net UserControls, **DMatViewer** and **XMatViewer**, that display real and complex matrix data on a form in a scrollable matrix format. These controls are for use in .Net Windows Form based applications. They cannot be used with Windows Asp.Net applications. The matrix viewer size, number of rows, number of columns, fonts and numeric format are all user programmable. The matrix viewers can display a number of rows and columns only limited the amount of free memory accessible by the program. A matrix viewer is read-only by default, but it can be made editable using the EnableEdit method.

DMatViewer

	0	1	2	3	4
0	0.84	0.47	0.13	0.32	0.20
1	0.25	0.22	0.39	0.10	0.83
2	0.86	0.04	0.90	0.58	0.13
3	0.86	0.38	0.46	0.47	0.39
4	0.85	0.73	0.31	0.64	0.81
5	0.49	1.00	0.91	0.62	0.81
6	0.14	0.89	0.89	0.36	0.31
7	0.85	0.38	0.58	0.26	0.43
8	0.76	0.76	0.38	0.86	0.74
9	0.75	0.67	0.09	0.07	0.40

Real Matrix

XMatViewer

	0
0	(9.69+0.00i)
1	(-0.89+0.88i)
2	(-0.89-0.88i)
3	(-1.08+0.00i)
4	(-0.80+0.57i)
5	(-0.80-0.57i)
6	(0.30+1.10i)
7	(0.30-1.10i)
8	(-0.41+0.79i)
9	(-0.41-0.79i)

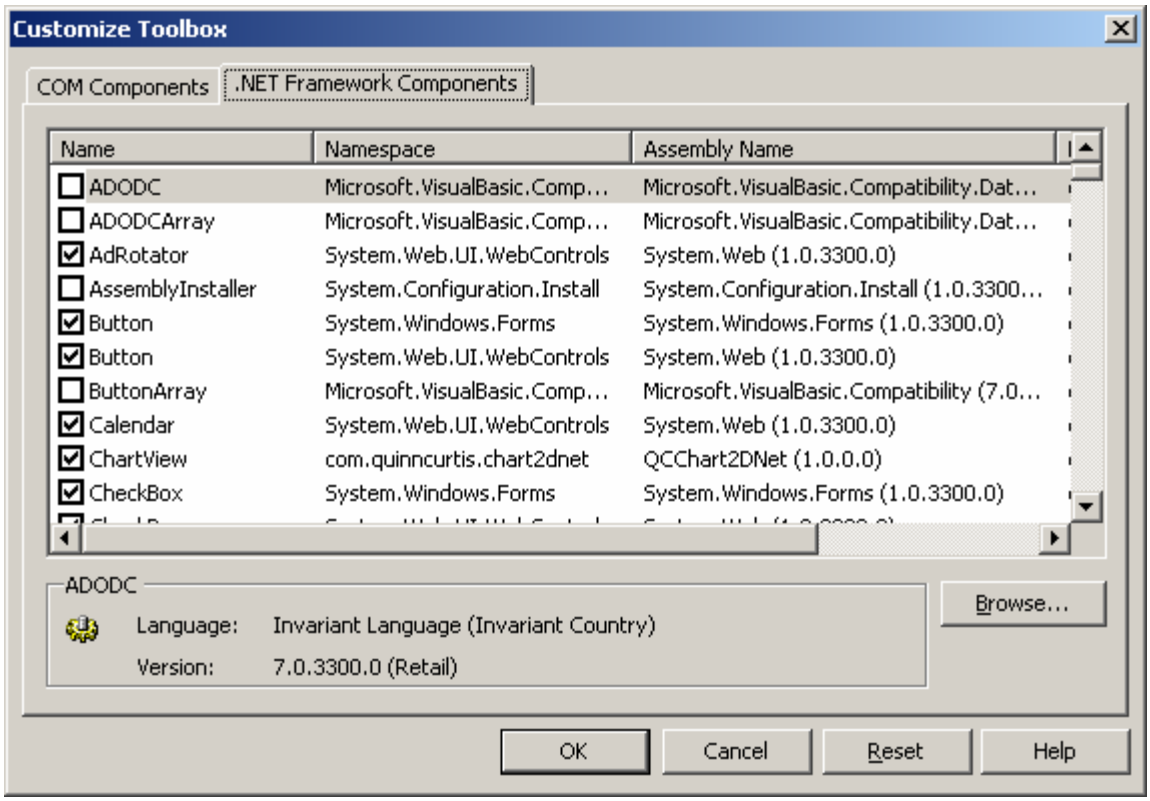
Complex Matrix

XMatViewer

	10	11	12
0	(-0.03-0.28i)	(-0.03+0.28i)	(0.01-0.58i)
1	(0.48-0.53i)	(0.48+0.53i)	(0.56-0.18i)
2	(1.00-0.00i)	(1.00+0.00i)	(-0.43+0.59i)
3	(-0.63+0.51i)	(-0.63-0.51i)	(-0.16-0.02i)
4	(-0.23-0.26i)	(-0.23+0.26i)	(-0.60-0.23i)
5	(0.50+0.20i)	(0.50-0.20i)	(0.06-0.24i)
6	(0.26-0.24i)	(0.26+0.24i)	(1.00-0.00i)
7	(-0.72+0.13i)	(-0.72-0.13i)	(0.07-0.02i)
8	(-0.71+0.63i)	(-0.71-0.63i)	(-0.85+0.13i)
9	(0.09+0.08i)	(0.09-0.08i)	(-0.39+0.14i)

Complex Matrix

Typically, you would add the matrix viewers to a .Net Form from the Visual Studio Toolbox. Add the controls to the Toolbox by right clicking on **Windows Forms** in the Toolbox window. Select **Customize Toolbox**. In the **Customize Toolbox** dialog, select the .Net Framework Components tab.



Click on Browse, navigate to the Quinn-Curtis\DotNet\lib folder, and select the QCMatViewNet.dll file that you will see in that folder. OK out of the **Customize Toolbox** dialog. You should now see the **DMatViewer** and **XMatViewer** controls under the **Windows Forms** tab of the Toolbox. Click on either control and drop it on a Windows form. Resize it to occupy the amount real estate you want to use.

Typical use of the matrix viewers do not have you using the constructors. You would normally add a matrix viewer to a form by dropping it from the Toolbox, which automatically calls the default constructor.

DMatViewer constructors

```
[Visual Basic]
Overloads Public Sub New( _
   ByVal mat As DMatBase, _
   ByVal rows As Integer, _
   ByVal cols As Integer _
)

[C#]
public DMatViewer(
   DMatBase mat,
   int rows,
   int cols
);
```

XMatViewer constructors

```
[Visual Basic]
Overloads Public Sub New( _
   ByVal mat As XMatBase, _
   ByVal rows As Integer, _
   ByVal cols As Integer _
)
[C#]
public XMatViewer(
   XMatBase mat,
   int rows,
   int cols
);
```

mat	The source matrix. **DMatViewer** uses a **DDMat** matrix while **XMatViewer** uses a **DXMat matrix**
row	The number of display rows in the matrix viewer.
cols	The number of display columns in the matrix viewer.

If you add a matrix viewer to a form from the Toolbox, initialize the viewer matrix, rows and columns using the **SetViewMatrix** method.

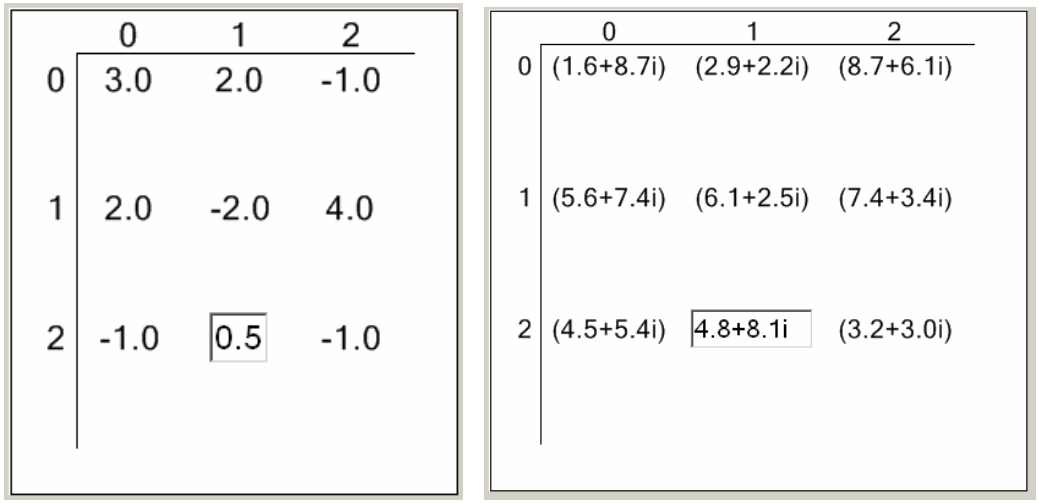
XMatViewer.SetViewMatrix Method

```
[Visual Basic]
Overloads Public Sub SetViewMatrix( _
   ByVal mat As DMatBase, _
   ByVal rows As Integer, _
   ByVal cols As Integer _
)
[C#]
public void SetViewMatrix(
   DMatBase mat,
   int rows,
   int cols
);
```

mat	The source matrix. **DMatViewer** uses a **DDMat** matrix while **XMatViewer** uses a **DXMat matrix**
row	The number of display rows in the matrix viewer.
cols	The number of display columns in the matrix viewer.

Set the decimal precision of the numeric values in the matrix viewer using the **Decimals** property. If you want to be able to edit the individual cells of a matrix, call the **EnableEdit(true)** method. If you make any changes to the properties of a matrix viewer, call the **UpdateDraw** method to force an immediate update. If the matrix viewer is edit enabled, click on the matrix element you want to edit. An edit box will appear in place of

the element. Make your edit and hit return, or click anywhere else in the matrix viewer. Any edits made to a matrix using a matrix viewer will immediately update the associated matrix; either a **DDMat** or **DXMat** object.



Above you see what the edit mode looks when the cell [2,1] is edited in real (DDMat) and complex (DXMat) matrices.

Example (Extracted from the EigenRealUnSym example program)

```
[C#]
dMatViewer1.SetViewMatrix(A,10,5);
dMatViewer1.DefaultNumericFont = new Font("SansSerif", 12, FontStyle.Regular);
dMatViewer1.EnableEdit(true);
dMatViewer1.UpdateDraw();
.
.
.
xMatViewer1.SetViewMatrix(EValues,10,1);
xMatViewer2.SetViewMatrix(EVectors,10,3);

xMatViewer1.Decimals = 2;
xMatViewer2.Decimals = 2;

xMatViewer1.UpdateDraw();
xMatViewer2.UpdateDraw();


[VB]
```

```
dMatViewer1.SetViewMatrix(A, 10, 5)
dMatViewer1.DefaultNumericFont = New Font("SansSerif", 12, FontStyle.Regular)
dMatViewer1.EnableEdit(True)
dMatViewer1.UpdateDraw()
.
.
.
xMatViewer1.SetViewMatrix(EValues, 10, 1)
xMatViewer2.SetViewMatrix(EVectors, 10, 3)

xMatViewer1.Decimals = 2
xMatViewer2.Decimals = 2

xMatViewer1.UpdateDraw()
xMatViewer2.UpdateDraw()
```

11. Thermocouple Linearization

TCLin

Thermocouples are the most widely used transducers for measuring temperature. They are economical, rugged and have stable characteristics over years. Further, available types can measure temperatures ranging from the cryogenic to jet exhaust.

Thermocouple devices are two pieces of metal in isothermal contact (physical contact at the same temperature). Because the number of free electrons in a metal depends on its temperature and composition, thermocouples exhibit a voltage potential that's a repeatable function of temperature. Over the past hundred years, several metallic pairs have become standard thermocouple types because of their accuracy and usefulness across common temperature ranges.

THERMOCOUPLES

Type	Composition	Temperature range, °
B	Pt-30% Rh versus Pt-6% Rh	0 to 1820
E	Ni-Cr alloy versus a Cu-Ni alloy	-270 to 1000
J	Fe versus a Cu-Ni alloy	-210 to 1200
K	Ni-Cr alloy versus Ni-Al alloy	-270 to 1372
N	Ni-Cr-Si alloy versus Ni-Si-Mg alloy	-270 to 1300
R	Pt-13% Rh versus Pt	-50 to 1768
S	Pt-10% Rh versus Pt	-50 to 1768
T	Cu versus a Cu-Ni alloy	-270 to 400

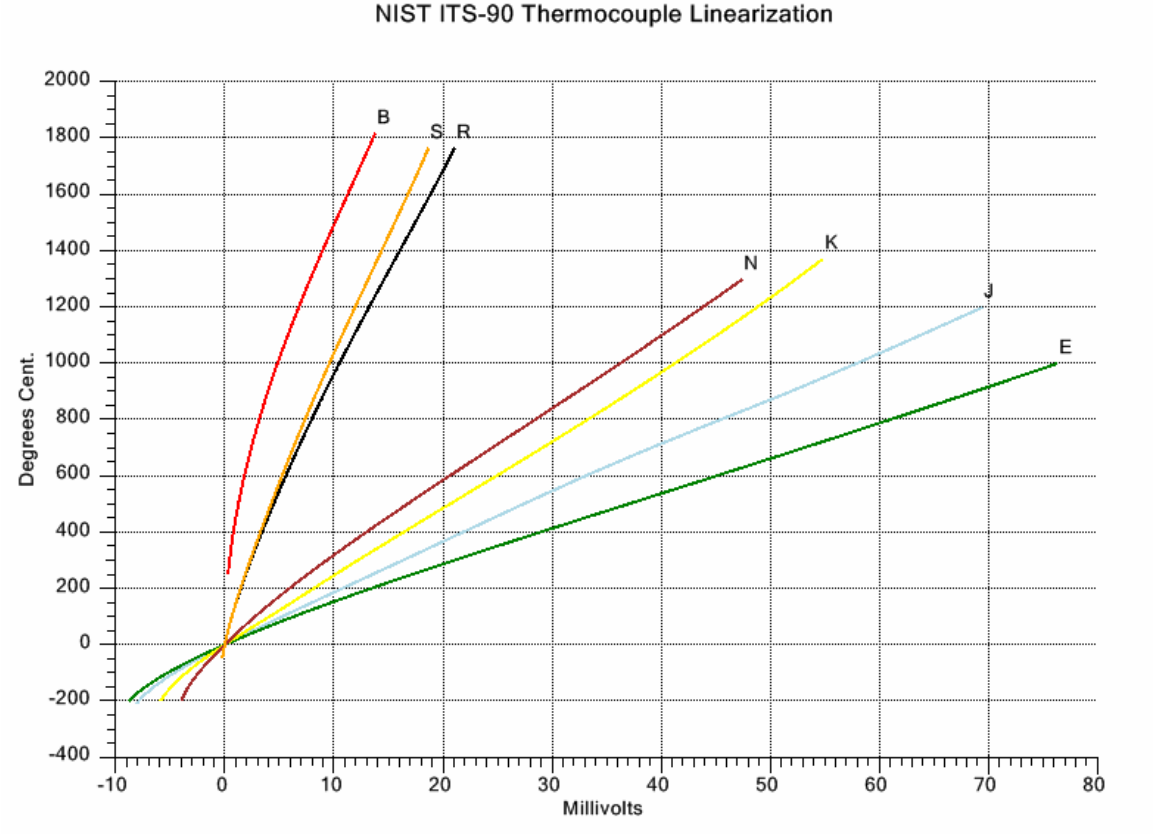
NIST ITS-90

The relationship between a thermocouple's output voltage and its temperature is a nonlinear function best approximated with a high-order polynomial. Once you measure a thermocouple's output voltage you can calculate a temperature by plugging the voltage into a polynomial equation or by looking up the voltage in standard thermocouple tables published by the National Bureau of Standards (NBS).

The thermocouple routines in this package are based on the reference tables summarized in NIST ITS-90 as published in the NIST Monograph 175. This standard defines 8 standard thermocouple types: B, E, J, K, N, R, S, T. Each of the 8 thermocouple types have one or more polynomial equations which define thermocouple voltage as a function of temperature.

It is important to understand that the thermocouple temperature to voltage tables presented in NIST ITS-90 are not from direct measurements. Thermocouple voltages were sampled at discrete intervals of temperature and equations fitted to these sampled

points. The NIST ITS-90 tables were generated from the fitted equation and not actual measured values.



The polynomial equations used to convert from volts to temperature, and temperature to volts, are those specified in the NIST ITS-90 tables. The implicit errors for the voltage to temperature conversions are listed below:

Temperature Sub range

	#1	#2	#3	#4
Thermocouple Type:	**J**			
Temperature Range:	-210 °C to 0 °C	0 °C to 760 °C	760 °C to 1200 °C	
Voltage Range:	-8.095 mV to 0 mV	0 mV to 42.919 mV	42.919 mV to 69.553 mV	
Error Range:	-0.05 °C to 0.03 °C	-0.04 °C to 0.04 °C	-0.04 °C to 0.03 °C	
Thermocouple Type:	**B**			
	250 °C to 700 °C	700 °C to 1820 °C		
Voltage Range:	0.291 to 2.431mV	2.431 mV to 13.820 mV		
Error Range:	-0.02 °C to 0.03 °C	-0.01 °C to 0.02 °C		

Thermocouple Type:	**E**			
	-200 °C to 0 °C	0 °C to 1000 °C		
Voltage Range:	-8.825 mV to 0 mV	0 mV to 76.373 mV		
Error Range:	-0.01 °C to 0.03 °C	-0.02 °C to 0.02 °C		

Thermocouple Type:	**K**		
Temperature Range:	-200 °C to 0 °C	0 °C to 500 °C	500 °C to 1372 °C
Voltage Range:	-5.891 mV to 0 mV	0 mV to 20.644 mV	20.644 mV to 54.886 mV
Error Range:	-0.02 °C to 0.04 °C	-0.05 °C to 0.04 °C	-0.05 °C to 0.06 °C

Thermocouple Type:	**N**		
Temperature Range:	-200 °C to 0 °C	0 °C to 600 °C	600 °C to 1300 °C
Voltage Range:	-3.990 to 0 mV	0 to 20.613 mV	20.613 to 47.513 mV
Error Range:	-0.02 °C to 0.03 °C	-0.02 °C to 0.03 °C	-0.04 °C to 0.02 °C

Thermocouple Type:	**R**			
Temperature Range:	-50 °C to 250 °C	250 °C to 1200 °C	1064 °C to 1664.5 °C	1664.5 °C to 1768.1 °C
Voltage Range:	-0.226 to 1.923 mV	1.923 to 13.228 mV	11.361 to 19.739 mV	19.739 to 21.103 mV
Error Range:	-0.02 °C to 0.02 °C	-0.005 °C to 0.005 °C	-0.0005 °C to 0.001 °C	-0.001 °C 0.002 °C to

Thermocouple Type:	**S**			
Temperature Range:	-50 °C to 250 °C	250 °C to 1200 °C	1064 °C to 1664.5 °C	1664.5 °C to 1768.1 °C
Voltage Range:	-0.235 to 1.874 mV	1.874 to 11.950 mV	10.332 to 17.536 mV	17.536 to 18.693 mV
Error Range:	-0.02 °C to 0.02 °C	-0.01 °C to 0.01 °C	-0.0002 °C to 0.0002 °C	-0.002 °C to 0.002 °C

Thermocouple Type:	**T**	
Temperature Range:	-200 °C to 0 °C	0 °C to 400 °C
Voltage Range:	-5.603 mV to 0 mV	0 mV to 20.872 mV
Error Range:	-0.02 °C to 0.04 °C	-0.03 °C to 0.03 °C

There are no errors in the temperature to voltage conversion conversions. Our routines use the temperature to voltage polynomials specified in NIST ITS-90. Those polynomials *define* the voltage to temperature curves. All errors are measured with respect to those curves.

Cold Junction Compensation

When making thermocouple measurements you must take into account the effect of the temperature of the terminal block, terminating the non-hot end of the thermocouple. This is referred to as cold-junction-compensation. Typically, this involves making a temperature measurement of the terminal block, using a non-thermocouple based measuring device, usually a solid-state temperature sensor (the Analog Devices AD590) or a precision thermistor. The terminal block temperature is converted to an equivalent

thermocouple voltage (use our **TempToMilliVolts** method) and the resulting voltage added to the measured thermocouple voltage. The *compensated* voltage, now a sum of the thermocouple voltage and the equivalent junction block voltage, is what you actually convert back to temperature using our **MilliVoltsToTemp** method. If you are not familiar with cold-junction-compensation, here is a good reference for you to study: http://www.maxim-ic.com/appnotes.cfm/an_pk/4026.

Class TCLin

The TCLin class provides methods to convert thermocouple millivolts into equivalent temperatures, and thermocouple temperatures into equivalent millivolts. The later conversion (temperature to millivolts) can be used in place of the Seebeck coefficient for use in the thermocouples cold-junction compensation calculations.

TCLin constructor

This constructor initializes the class for a specific thermocouple type. Use one of the thermocouple, TCLin.TC_TYPE, type constants: J, B, E, K, N, R, S, T.

```
[Visual Basic]
Overloads Public Sub New( _
   ByVal tct As TC_TYPE _
)
[C#]
public TCLin(
   TC_TYPE tct
);
```

Parameters

tct Thermocouple type. Use one of the thermocouple, TCLin.TC_TYPE, type constants: J, B, E, K, N, R, S, T.

Once the class is instantiated for a specific thermocouple, call the **MilliVoltsToTemp** method to convert thermocouple millivolts into a temperature (degrees Centigrade) and **TempToMilliVolts** to convert a thermocouple temperature into millivolts (used in cold-junction compensation).

Method TCLin.MilliVoltsToTemp

Convert thermocouple millivolts to temperature in degrees Centigrade.

```
[Visual Basic]
Public Function MilliVoltsToTemp( _
   ByVal mv As Double _
) As Double
```

```
[C#]
public double MilliVoltsToTemp(
   double mv
);
```

Parameters

mv Thermocouple voltage in millivolts.

Return Value

Returns the thermocouple temperature in degrees Centigrade.

Method TCLin.MilliVoltsToTempIterative

Convert thermocouple millivolts to temperature in degrees Centigrade. This is the ultimate in voltage to temperature conversion for a thermocouple. It first uses the **MilliVoltsToTemp** method to provide an initial estimate. Then it backward iterates on the on the temperature to millivolts polynomials, for which there is zero error, using the Newton-Raphson of root solving. This ends up by returning a millivolts to temperature conversion accurate to at least the specified tolerance.

```
[Visual Basic]
Public Function MilliVoltsToTempIterative( _
   ByVal mv As Double _
   ByVal tolerance As Double _
) As Double
[C#]
public double MilliVoltsToTempIterative(
   double mv
   double tolerance
);
```

Parameters

mv Thermocouple voltage in millivolts.

tolerance Iterations are carried out until the tolerance level is reached. Because the Newton-Raphson method converges extremely fast, typically the accuracy of the conversion is 3 – 6 orders of magnitude more accurate than the tolerance. The minimum tolerance that you can specify is 10e-10.

Return Value

Returns the thermocouple temperature in degrees Centigrade.

Method TCLin.TempToMilliVolts

Convert thermocouple temperature to millivolts.

```
[Visual Basic]
Public Function TempToMilliVolts( _
   ByVal temp As Double _
) As Double

[C#]
public double TempToMilliVolts(
   double temp
);
```

Parameters

temp Thermocouple temperature in degrees Centigrade.

Return Value

Returns the thermocouple voltage in millivolts.

There are also simple methods (**GetMinMilliVolts, GetMaxMilliVolts, GetMinTemp,** and **GetMaxTemp**) that return the minimum and maximum voltages and temperatures associated with a given thermocouple type.

Example

The example program TCLinTest divides each thermocouple voltage range into 10,000 equal segments and calculates the **MilliVoltsToTemp** conversion for each point. It then feeds the resulting temperature back to the **TempToMilliVolts** method, and compares the resulting millivolt measurement to the original and remembers the maximum error. This represents a good test of the overall accuracy of the linearization routines, since the **MilliVoltsToTemp** and **TempToMilliVolts** methods used different linearization polynomials.

```
[C#]
TCLin.TC_TYPE tci = TCLin.TC_TYPE.J;

TCLin tc = new TCLin( tci);
double mV= tc.GetMinMilliVolts(), mv2 = 0.0;
double temp = 0.0;
int count = 10000;
double voltageInc = (tc.GetMaxMilliVolts() - tc.GetMinMilliVolts())/count;
double maxerror = 0.0, error = 0;
for (int i=0; i < count; i++)
{
    temp = tc.MilliVoltsToTemp(mV);
```

```
    mv2 = tc.TempToMilliVolts(temp);
    error = Math.Abs(mV - mv2);
    if (error > maxerror)
        maxerror = error;
    if (error >0.1)
        break;
    mV += voltageInc;
}
```

```
[VB]
Dim tc As New TCLin(tci)
Dim mV As Double = tc.GetMinMilliVolts()
Dim mv2 As Double = 0.0
Dim temp As Double = 0.0
Dim count As Integer = 5000
Dim voltageInc As Double = (tc.GetMaxMilliVolts() - tc.GetMinMilliVolts()) / count
' in mV
Dim maxerror As Double = 0.0
Dim [error] As Double = 0

Dim i As Integer
For i = 0 To count - 1
  temp = tc.MilliVoltsToTemp(mV);
  ' temp = tc.MilliVoltsToTempIterative(mV, 0.001)
   mv2 = tc.TempToMilliVolts(temp)
   [error] = Math.Abs((mV - mv2))
   If [error] > maxerror Then
      maxerror = [error]
   End If
   If [error] > 0.1 Then
      Exit For
   End If
    mV += voltageInc
Next i
```

A more practical method would simulate an actual thermocouple measurement, with cold-junction-compensation.

```
[C#]
// This would be replaced by your own routine that reads uses a voltmeter or A/D
// converter to read the thermocouple voltage.
double GetThermocoupleMilliVolts()
{
    double tcmv = 10.1; //millivolts
```

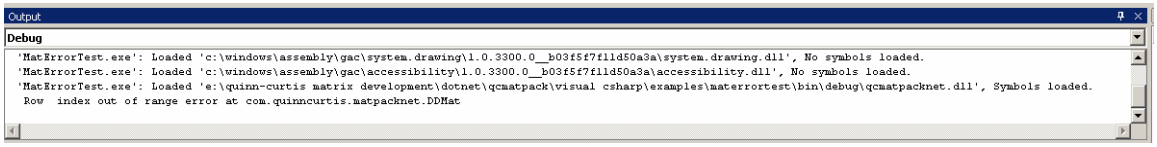
```
    return tcmv;
}

// This would be replaced by your own routine that reads uses a voltmeter or A/D
// converter to read the cjc temperature.
double GetCJCTemperature()
{
    double cjctemp = 16.3; //degrees Cent.
    return cjctemp;
}

public double TCLinearizeWithCJC(TCLin.TC_TYPE tci)
{
    TCLin.TC_TYPE tct = TCLin.TC_TYPE.K;

    TCLin tc = new TCLin( tct);
    // You would need to implement the routine GetThermocoupleMilliVolts();
    double tcMilliVolts = GetThermocoupleMilliVolts();
    // You would need to implement the routine GetCJCTemperature ();
    double cjcTemp = GetCJCTemperature();

// Convert terminal block temperature to equivalent thermocouple millivolts
    double cjcEquivMilliVolts = tc.TempToMilliVolts(cjcTemp);

    // Add the cjc millivolts to the thermocouple millivolts
    tcMilliVolts += cjcEquivMilliVolts;
    // Convert the cjc compensated millivolts to temperature
    double tcTemperature = tc.MilliVoltsToTemp(tcMilliVolts);
    return tcTemperature;
}

[VB]
Function GetThermocoupleMilliVolts() As Double
   Dim tcmv As Double = 10.1 'millivolts
   Return tcmv
End Function 'GetThermocoupleMilliVolts


Function GetCJCTemperature() As Double
   Dim cjctemp As Double = 16.3 'degrees Cent.
   Return cjctemp
End Function 'GetCJCTemperature
```

```
Public Function TCLinearizeWithCJC() As Double
    Dim tct As TCLin.TC_TYPE = TCLin.TC_TYPE.K

    Dim tc As New TCLin(tct)
    ' You would need to implement the routine GetThermocoupleMilliVolts();
    Dim tcMilliVolts As Double = GetThermocoupleMilliVolts()
    ' You would need to implement the routine GetCJCTemperature ();
    Dim cjcTemp As Double = GetCJCTemperature()

    ' Convert terminal block temperature to equivalent thermocouple millivolts
    Dim cjcEquivMilliVolts As Double = tc.TempToMilliVolts(cjcTemp)

    ' Add the cjc millivolts to the thermocouple millivolts
    tcMilliVolts += cjcEquivMilliVolts
    ' Convert the cjc compensated millivolts to temperature
    Dim tcTemperature As Double = tc.MilliVoltsToTemp(tcMilliVolts)
    Return tcTemperature
End Function 'TCLinearizeWithCJC
```

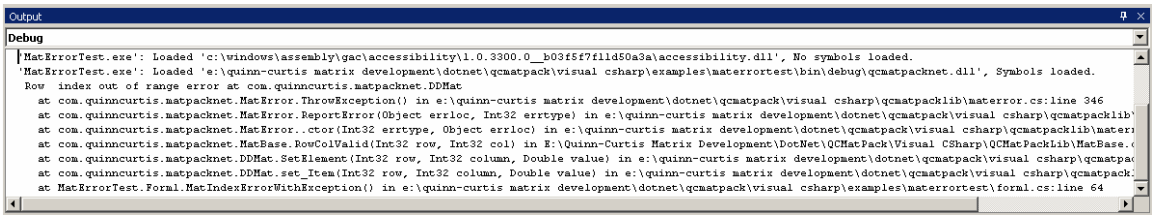
12. Error Handling

The matrix math classes and numerical algorithm classes can generate a limited number of runtime errors. Any time an error is detected, an object **MatError** object is created, and that object processes the error. The **MatError** object can process the error in several different ways. It can print an error message to a message box on the screen,

print an error message to the system console,


Output
Debug
'MatErrorTest.exe': Loaded 'c:\windows\assembly\gac\system.drawing\1.0.3300.0__b03f5f7f11d50a3a\system.drawing.dll', No symbols loaded.
'MatErrorTest.exe': Loaded 'c:\windows\assembly\gac\accessibility\1.0.3300.0__b03f5f7f11d50a3a\accessibility.dll', No symbols loaded.
'MatErrorTest.exe': Loaded 'e:\quinn-curtis matrix development\dotnet\qcmatpack\visual csharp\examples\materrortest\bin\debug\qcmatpacknet.dll', Symbols loaded.
Row index out of range error at com.quinncurtis.matpacknet.DDMat

throw and exception which you can trap and process in your own way,


Output
Debug
'MatErrorTest.exe': Loaded 'c:\windows\assembly\gac\accessibility\1.0.3300.0__b03f5f7f11d50a3a\accessibility.dll', No symbols loaded.
'MatErrorTest.exe': Loaded 'e:\quinn-curtis matrix development\dotnet\qcmatpack\visual csharp\qcmatpacklib\materror.cs:line 346
at com.quinncurtis.matpacknet.MatError.ReportError(Object errloc, Int32 errtype) in e:\quinn-curtis matrix development\dotnet\qcmatpack\visual csharp\qcmatpacklib
at com.quinncurtis.matpacknet.MatBase.RowColValid(Int32 row, Int32 col) in E:\Quinn-Curtis Matrix Development\DotNet\QCMatPack\Visual CSharp\QCMatPackLib\MatBase.
at com.quinncurtis.matpacknet.DDMat.SetElement(Int32 row, Int32 column, Double value) in e:\quinn-curtis matrix development\dotnet\qcmatpack\visual csharp\qcmatpa
at com.quinncurtis.matpacknet.DDMat.set_Item(Int32 row, Int32 column, Double value) in e:\quinn-curtis matrix development\dotnet\qcmatpack\visual csharp\qcmatpack
at MatErrorTest.Form1.MatIndexErrorWithException() in e:\quinn-curtis matrix development\dotnet\qcmatpack\visual csharp\examples\materrortest\form1.cs:line 64

ignore the error, or exit the program.

The standard errors that the software generates are listed below:

Error Constant	Description	Exception (if enabled)
NOERR	No error	
MAT_COL_ERR	Column index out of range error	System.IndexOutOfRangeException
MAT_ROW_ERR	Row index out of range error	System.IndexOutOfRangeException
MAT_ELEMENT_ERR	Array Element Error;	System.IndexOutOfRangeException
INVALID_INDEX	Array Index Exceeds Dimension	System.IndexOutOfRangeException
NOMEM	Not Enough Memory	System.OutOfMemoryException
NULLMAT	Null matrix argument error	System.ArgumentNullException
INVALID_ARG_DIM	Dimensions Do Not Match	System.RankException
INVALID_MAT_DIM	Matrix should have the same number of rows and columns	System.RankException
SYMMETRIC_MATRIX_REQUIRED	Matrix must be symmetric, ie. A = Transpose(A)	System.RankException
POSDEFINITE_MATRIX_REQUIRED	Matrix must be positive definite.	System.RankException
HERMITIAN_MATRIX_REQUIRED	Matrix must be Hermitian	System.RankException
NO_DSPACE	Insufficient Disk Space	System.IO.IOException
FILE_ERROR	File Read/Write Error	System.IO.IOException
INVALID_FILENAME	Invalid file name	System.IO.FileNotFoundException
SINGULAR	Matrix Is Singular	Does not throw and exception
NO_ACC	Solution Is Not Accurate	Does not throw and exception

Select the error processing method that you want by setting the static

MatError.ReportMode property to one of the report mode constants:

```
public enum ErrorReportModes {
        DO_NOTHING,
        SYSTEM_CONSOLE,
        MESSAGE_BOX,
        THROW_EXCEPTION,
        EXIT};
```

The default is error reporting mode is MatError.ErrorReportModes.MESSAGE_BOX

The example below is extracted from the MatErrorTest example program and demonstrates the use of runtime exception error processing using try/catch blocks.

```
[C#]
public void MatIndexErrorWithException()
{
    try
    {
```

```
        int m = 2, n = 20;
        DDMat A = new DDMat(m, n);
        for (int i=0; i < m; i++)
            for (int j=0; j < n; j++)
                A[i,j] = i + n + j;
        A[2,12] = 22; // generates a row index out of range error
    }
    catch (System.IndexOutOfRangeException exp)
    {
        string s = exp.StackTrace.ToString();
        System.Console.Write(s);
    }
}
```

[VB]

```
Private Sub button4_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles button4.Click
   Try
     Dim errtype As Integer = GetErrorTest()
     GenerateError(errtype, MatError.ErrorReportModes.THROW_EXCEPTION)
     Catch exp As System.IndexOutOfRangeException
        Dim s As String = exp.StackTrace.ToString()
        System.Console.Write(s)
   End Try
 End Sub
```

13. Using QCMatPack for *.Net* to Create Windows and Asp.Net Applications

(*** Critical Note ***) Running the Example Programs

The example programs for **QCMatPack** charting software are supplied in complete source. In order to save space, they have not been pre-compiled which means that many of the intermediate object files needed to view the main form are not present. This means that matrix viewer controls (**DMatViewer** and **XMatViewer**) will not be visible on the main Form if you attempt to view the main form before the project has been compiled. The default state for all of the example projects should be the Start Page. Before you do view any other file or form, do a build of the project. This will cause the intermediate files to be built. If you attempt to view the main Form before building the project, Visual Studio decides that the matrix viewer controls placed on the main form do not exist and deletes them from the project.

Follow the following steps in order to incorporate the **QCMatPack** classes into your program. This is not the only way to add charts to an application. We found the technique described below this to be the most flexible.

Install the matrix viewers in the Visual Studio Toolbox

Most all of the example programs use one or more of the matrix viewers (**DMatViewer** or **XMatViewer**), so you need to install them in the Visual Studio Toolbox. Display the Toolbox (View | Toolbox), and right click on **Windows Forms** in the Toolbox window. Select **Customize Toolbox**. In the **Customize Toolbox** dialog, select the .Net Framework Components tab. Click on Browse, navigate to the Quinn-Curtis\DotNet\lib folder, and select the QCMatViewNet.dll file that you will see in that folder. OK out of the **Customize Toolbox** dialog. You should now see the **DMatViewer** and **XMatViewer** controls under the **Windows Forms** tab of the Toolbox.

Visual Basic for .Net

If you do not already have an application program project, create one using the Visual Studio project wizard (**File | New | Project | Visual Basic Projects | Windows Application**). On the left select a project type of **Visual Basic Projects**. Give the project a unique name (our version of this example is **QCMatPackExample1**). You will end with a basic Form based application. For purposes of this example, the chart will placed in the initial, default form.

- Right click on Reference in the Solution Explorer window and select **Add Reference**. Browse to the Quinn-Curtis/DotNet/lib subdirectory and select the **QCMatPackNet.DLL**. Next, view the **Form1.vb** code

- ***Critical Step:*** Make sure you add a reference to the QCMatPack namespace in any source file where you want to use the QCMatPack classes. Do this by adding a reference to **com.quinncurtis.matpacknet** at the top of the source file.

```
Imports com.quinncurtis.matpacknet
```

- Now you can use any of the QCMatPack classes in your program. Should you want to use one or more of the matrix viewers (**DMatViewer** and **XMatViewer**) in your program, drag and drop the appropriate control from the Toolbox. See the TestMat method in the **QCMatPackExample1** program for an example.

```
Sub TestQCMatPack()
    Dim aData As Double(,) = {{3, 2, -1}, {2, -2, 4}, {-1, 0.5, -1}}
    Dim bData As Double() = {1, -2, 0}

    Dim A As New DDMat(aData)
    Dim b As New DDMat(bData)

    Dim x As New DDMat()
    A.LES_Solve(b, x)
End Sub 'TestQCMatPack
```

If you wish to add the QCMatPack routines to an ASP.Net program, follow the same steps described above, except create an ASP.Net Web Application project instead of a Windows Application project. Add the **QCMatPackNet.DLL** file to the references section in the same way, and include a reference to **com.quinncurtis.matpacknet** to the **Imports** section of the file where you use the routines. We have included a simple WebForm1.aspx example form in the Examples\ASPNetExample folder. We can't provide you with a working project though. You will need to create that on your own, using your own web site to hold the files.

Visual C# for .Net

If you do not already have an application program project, create one using the Visual Studio project wizard (**File | New | Project | Visual Basic Projects | Windows Application**). On the left select a project type of **Visual C# Projects**. Give the project a unique name (our version of this example is **QCMatPackExample1**). You will end with a basic Form based application. For purposes of this example, the chart will placed in the initial, default form.

- Right click on Reference in the Solution Explorer window and select **Add Reference**. Browse to the Quinn-Curtis/DotNet/lib subdirectory and select the **QCMatPackNet.DLL**. Next, view the **Form1.cs** code

- ***Critical Step:*** Make sure you add a reference to the QCMatPack namespace in any source file where you want to use the QCMatPack classes. Do this by adding a reference to **com.quinncurtis.matpacknet** at the top of the source file.

```
using com.quinncurtis.matpacknet;
```

- Now you can use any of the QCMatPack classes in your program. Should you want to use one or more of the matrix viewers (**DMatViewer** and **XMatViewer**) in your program, drag and drop the appropriate control from the Toolbox. See the TestMat method in the **QCMatPackExample1** program for an example.

```
void TestQCMatPack()
{
    double [,] aData = {{3,2,-1},{2,-2,4},{-1, 0.5, -1}};
    double [] bData = {1, -2, 0};

    DDMat A = new DDMat(aData);
    DDMat b = new DDMat(bData);

    DDMat x = new DDMat();
    A.LES_Solve(b,x);
}
```

If you wish to add the QCMatPack routines to an ASP.Net program, follow the same steps described above, except create an ASP.Net Web Application project instead of a Windows Application project. Add the **QCMatPackNet.DLL** file to the references section in the same way, and include a reference to **com.quinncurtis.matpacknet** to the **using** section of the file where you use the routines. We have included a simple WebForm1.aspx example form in the Examples\ASPNetExample folder. We can't provide you with a working project though. You will need to create that on your own, using your own web site to hold the files.

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